AFFTC-TIM-05-04

LIMITED EVALUATION OF A RELATIVE GPS DATALINK BETWEEN TWO C-12C AIRCRAFT

(PROJECT "LOST WINGMAN")

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FINAL TECHNICAL INFORMATION MEMORANDUM

AIR FORCE FLIGHT TEST CENTER
EDWARDS AIR FORCE BASE, CALIFORNIA
AIR FORCE MATERIAL COMMAND
UNITED STATES AIR FORCE

This Technical Information Memorandum (AFFTC-TIM-05-04, Limited Evaluation of a Relative GPS Datalink Between Two C-12C Aircraft, Project "LOST WINGMAN") was prepared and submitted under Job Order Number M04C0400 by the LOST WINGMAN test team, US Air Force Test Pilot School (USAFTPS), Edwards Air Force Base, CA 93524-6485.

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14. ABSTRACT
This report presents the results of a limited evaluation of a relative GPS datalink system installed onboard two USAF C-12C aircraft. This project was a risk reduction step to test the stability of the datalink to provide relative position and attitude information from a lead aircraft to a trail aircraft for the potential purpose of autonomous aerial refueling. Testing began on 11 Apr 05 and was completed on 2 May 05 after two two-ship formation flights. Relative position accuracy data between the two GPS receiver antennas were compared to GPS Aided Inertial Reference (GAINR) truth source data. The attitude data of the Micro-Electro-Mechanical System (MEMS) Inertial Measurement Unit (IMU) in the lead aircraft were also compared to the GAINR Embedded GPS/Inertial Navigation System (EGI).

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Lost Wingman Test Team

EXECUTIVE SUMMARY

The US Air Force Test Pilot School (TPS) class 04B Lost Wingman Test Management Project (TMP) group accomplished flight testing of a relative differential Global Positioning System (GPS) datalink between two C-12C aircraft. This test project was conducted at the request of the Air Force Institute of Technology, Department of Electrical and Computer Engineering (AFIT/ENG). All testing was accomplished under TPS Job Order Number M05C7000. A total of 8.9 hours were flown on two flight test sorties in the R-2508 complex from 11 April to 2 May 2005.

Two Air Force Flight Test Center (AFFTC), 412th Test Wing (TW), Raytheon C-12C Huron twin-engine turboprop transport aircraft, tail #73-1215 and #70-00158 were the test aircraft. The system under test (SUT) consisted of a datalink antenna, Ultra High Frequency (UHF) datalink transceiver, GPS receiver, Micro-Electro-Mechanical System Inertial Measurement Unit (MEMS IMU), and datalink computer and software on the lead aircraft; and a datalink antenna, datalink transceiver, GPS receiver, and datalink computer and software on the trail aircraft. Two Linux based laptops were provided to interface with the SUT installed on each aircraft.

Flight test support hardware was provided by the TPS Special Instrumentation branch. The 412th Test Wing, Range Support Division (412 TW/ENR) provided a GPS Aided Inertial Reference System (GAINR) system with an Embedded GPS Inertial Navigation System (EGI) for aircraft tail #73-1215 and a GAINR-Lite system for aircraft tail #70-00158.

The test team successfully performed a limited evaluation of the relative GPS datalink. This test program demonstrated that a low cost GPS and MEMS IMU with a datalink could provide real-time relative position and attitude information between an aircraft formation. The system had deficiencies in datalink functionality, attitude accuracy, and noise that must be overcome prior to future use in autonomous aircraft applications. However, the system demonstrated potential for use during autonomous aerial refueling with improved performance and reliability and was capable of supporting follow-on testing with limitations due to the observed deficiencies.

Ground Checkout of Lead Aircraft

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Test team member moving GPS antenna during ground checkout

INTRODUCTION

Background

The Lost Wingman test effort was a risk reduction step in an autonomous aerial refueling proof of concept demonstration. A follow-on USAF Test Pilot School (TPS) Test Management Project (TMP) will use the datalink as a control input for a CALSPAN Corporation Variable Stability Learjet 24/25 flying autonomously in formation behind a C-12C.

The Lost Wingman Test Team from the USAF TPS at Edwards AFB, CA performed ground and flight testing of a relative GPS position datalink installed onboard two C-12C aircraft. The test team investigated the functionality of the datalink, the accuracy of the relative position solution, and the accuracy of the attitude solution provided by the test system in reference to a Time Space Position Information (TSPI) truth source. In the follow-on TMP, the GPS and attitude information from the lead aircraft will be transmitted over the datalink to determine the position where the autonomous vehicle must fly.

The Lost Wingman TMP was conducted at the request of the Air Force Institute of Technology, Department of Electrical and Computer Engineering (AFIT/ENG). The Responsible Test Organization (RTO) for this project was the 412th Test Wing. The USAF TPS Lost Wingman Test Team acted as the executing organization as directed by the Commandant, USAF TPS. All testing was accomplished under TPS Job Order Number M05C7000. A total of 8.9 hours of flight test were flown on two two-ship formation sorties using C-12C aircraft in the R-2508 complex from 11 April to 2 May 2005.

Program Chronology

Aircraft modifications were completed on 6 April 2005. Flight testing was conducted between 11 April 2005 and 2 May 2005.

Test Item Description

The system under test (SUT) consisted of a datalink antenna, datalink transceiver, GPS receiver, Micro-Electro-Mechanical System Inertial Measurement Unit (MEMS IMU), and datalink computer and software on the lead aircraft. A datalink antenna, datalink transceiver, GPS receiver, and datalink computer and software completed the SUT on the trail aircraft. Attitude and GPS information from the lead aircraft were passed through the datalink at a 20 Hz data rate to the trail aircraft. The trail test item received the datalink signal from the lead aircraft, calculated the relative position of the trail aircraft, and stored the MEMS IMU data.

Specialized software was designed and loaded onto the datalink computers to collect information from the GPS receiver, datalink transceiver, and MEMS IMU, and determine the relative position and attitude solution. Appendix 1 contains a detailed test

item description including the manufacturer, and model or part numbers of the SUT components. Figure 1 illustrates the SUT and the original components provided by the client.

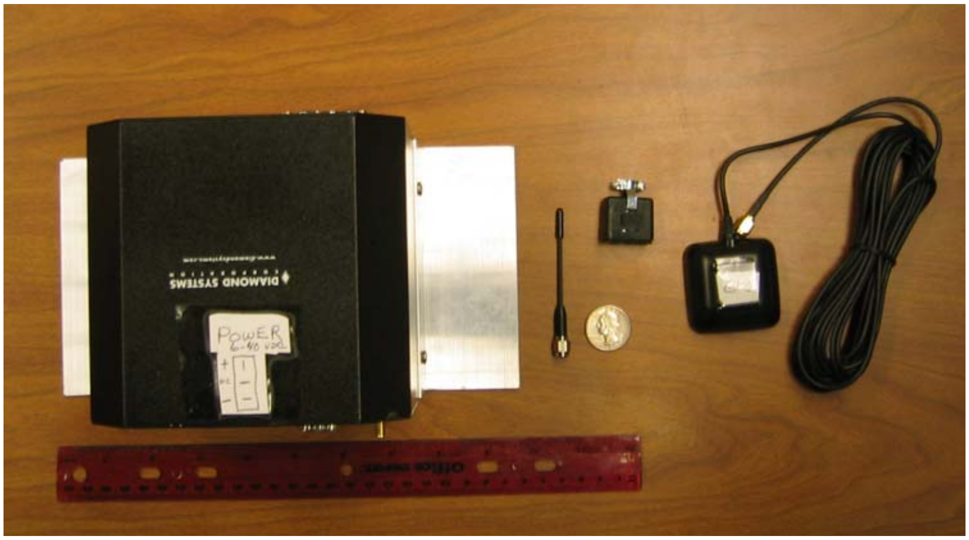

Figure 1: Lost Wingman System with original datalink and GPS antennae

Test Team

The test team consisted of five members of TPS Class 04B at the USAF Test Pilot School. Two team members were pilots and three team members were flight test engineers with all team members participated in the flight testing.

Test Objectives

The overall test objective was to perform a limited evaluation of the relative GPS datalink system between two C-12 aircraft. The evaluation was broken into three specific objectives:

1. Demonstrate the accuracy of the relative position solution
2. Observe the accuracy of the Micro-Electro-Mechanical System Inertial Measurement Unit (MEMS IMU)
3. Observe the datalink functionality

All test objectives were met.

Limitations

There were no limitations.

TEST AND EVALUATION

General

The overall test objective was to perform a limited evaluation of the relative GPS datalink system between two C-12 aircraft. The evaluation was broken into three objectives, demonstrating the accuracy of the relative position solution, observing the accuracy of the Micro-Electro-Mechanical System Inertial Measurement Unit (MEMS IMU) attitude solution, and observing the datalink functionality. Approximately 10 hours of ground test to verify system functionality were accomplished prior to flight test. A total 8.9 hours of flight time on two two-ship C-12C formation flights were flown in the R-2508 complex from 11 April 2005 to 2 May 2005 to accomplish the test objectives.

Relative Position Solution Accuracy

This test objective was to demonstrate the Lost Wingman System Under Test (SUT) relative GPS position solution accuracy.

Procedures

The relative position was defined as the difference between the positions of the GPS antennae, mounted on the top of the C-12C horizontal tails, measured in the North, East, Down reference frame. Raw GPS data from the lead aircraft were sent to the trail aircraft where the SUT used this GPS data and GPS data from the trail aircraft to calculate a relative position solution. This solution was calculated and displayed real-time on the developer provided laptop and stored in data files on the trail aircraft SUT. The actual GPS position of the aircraft was not displayed real-time, but the raw GPS data were stored to the SUT for post-flight analysis. The truth source for flight testing was the relative position solution in the North, East, Down reference frame calculated post-flight using the GPS information from the GPS Aided Inertial Reference (GAINR) system on the lead aircraft and a GAINR-Lite system on the trail aircraft.

Ground testing was performed on 13 April 05 to verify proper SUT operation. During ground test, the distance between the two GPS antennae was measured with a tape measure.

During post-flight data analysis the accuracy of the relative position solution was determined in the pre-contact, contact, and observation positions in addition to transitions from observation to pre-contact, pre-contact to observation, pre-contact to contact, and contact to pre-contact positions. These C-12C formation flight positions are described in Appendix C. Each position (pre-contact, contact, and observation) were flown for a minimum of 120 seconds to collect sufficient data. Each of the aforementioned transitions was flown twice to collect sufficient data. Aircraft configuration for all test points was gear and flaps up. The propeller speed was 1700 rpm, a standard cruise propeller setting. The maneuvers were flown in the data band of

190 ± 5 KIAS and 10,000 ± 100 feet pressure altitude as these were the flight conditions for follow-on testing with the Learjet flying autonomously in formation behind a C-12C.

Time histories of the position of the trail GPS antenna relative to the lead GPS antenna in North, East, Down coordinates were calculated by subtracting the position of the lead aircraft GPS antenna from the trail aircraft GPS antenna. The relative position was then converted from the North, East, Up reference frame to North, East, Down reference frame. The error in the SUT relative solution was then calculated by subtracting the truth relative position from the SUT relative position solution.

Results

Fourteen minutes of data were collected during ground tests with the aircraft positioned such that the distance and direction between the two GPS antennae could be accurately measured. The radial distance was physically measured to be 74.25 feet, and the SUT calculated distance was 74.2 feet for an error of less than one inch.

A summary of the relative GPS accuracy results for each maneuver is depicted in Table 1. Associated North, East, Down position and North, East, Down error plots are displayed in figures D-1 to D-16. The relative GPS position solution component was considered satisfactory if the error was within ± 2 feet of the truth source during all flight test maneuvers. Error exceeding ± 2 feet from the truth source was deemed unsatisfactory.

Table 1: Summary of SUT Relative Position Results

Maneuver/Position	North Error	East Error	Down Error	Radial Error
	Maximum Error in feet			
Ground Test	N/A	N/A	N/A	0.1
Straight & Level Unaccelerated Flight (SLUF)	-0.95	1.97*	-1.13	-1.75*
Observation	-0.64	1.62	-1.13	-0.56
Pre-contact	-0.95	1.53	0.81	-1.32
Contact	-0.75	0.91	0.38	-0.92
Observation → Pre-contact	0.63	1.97	0.76	-1.75
Pre-contact → Observation	**-2.01***	**2.35**	-1.53	-1.06
Pre-contact → Contact	-0.99	1.01	-0.44	-1.15
Contact → Pre-contact	-0.92	0.95	-0.29	-1.05
Overall	**Satisfactory**	**Unsatisfactory**	**Satisfactory**	**Satisfactory**
*Maximum occurred due to checksum error and therefore was considered satisfactory Satisfactory (within ±2 feet of truth source during the entire maneuver). Unsatisfactory (otherwise)				

The SUT achieved relative position accuracy within the two-foot GAINR accuracy during all maneuvers except during the maneuver from pre-contact to observation. During this maneuver, the East error exceeded the ± 2 feet bounds for approximately 27 seconds as illustrated in Figure 2.

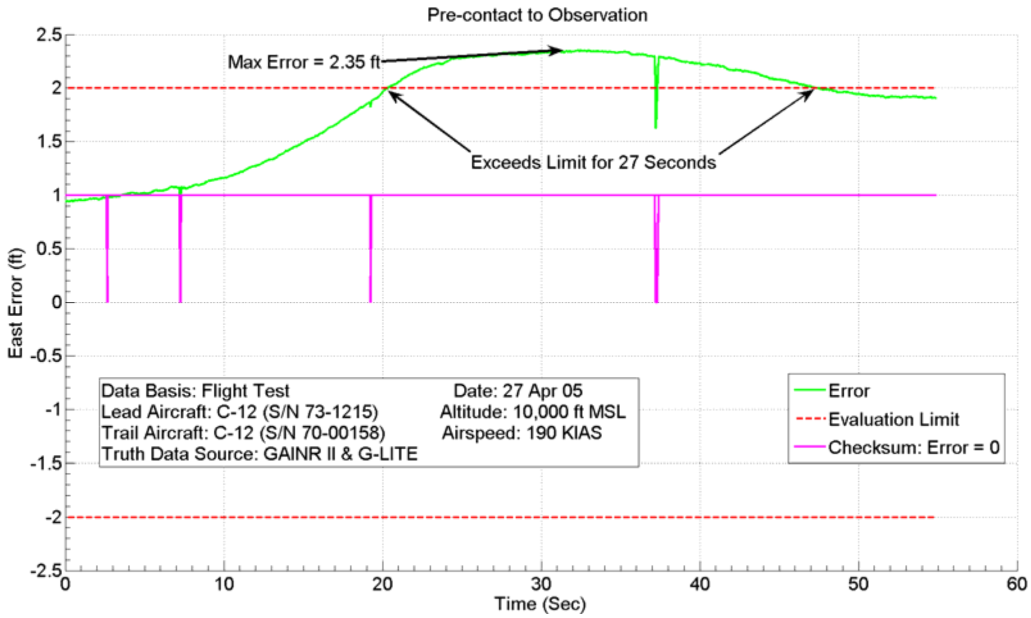

Figure 2: East Error During Pre-contact → Observation Maneuver

During this maneuvering, the trail aircraft was at a range of 200 to 250 feet from the lead aircraft. The primary cause of this error was not identified by the test team as errors of this magnitude were not present during other maneuvers at similar ranges. However, the effect of this 2.35 foot error while controlling a trail aircraft at this range would be fairly minimal. It would lead to a position offset of less than 1%. As there was a gradual increase and decrease in error, it would not be expected to cause uncommanded dynamic maneuvering of a trail aircraft during follow-on testing.

During the same maneuver, the North component exceeded the ± 2 feet bounds due to a completely different phenomenon. A checksum error caused a jump in error for one time step of 0.05 seconds, causing the error to exceed the ± 2 feet bound as illustrated in Figure 3.

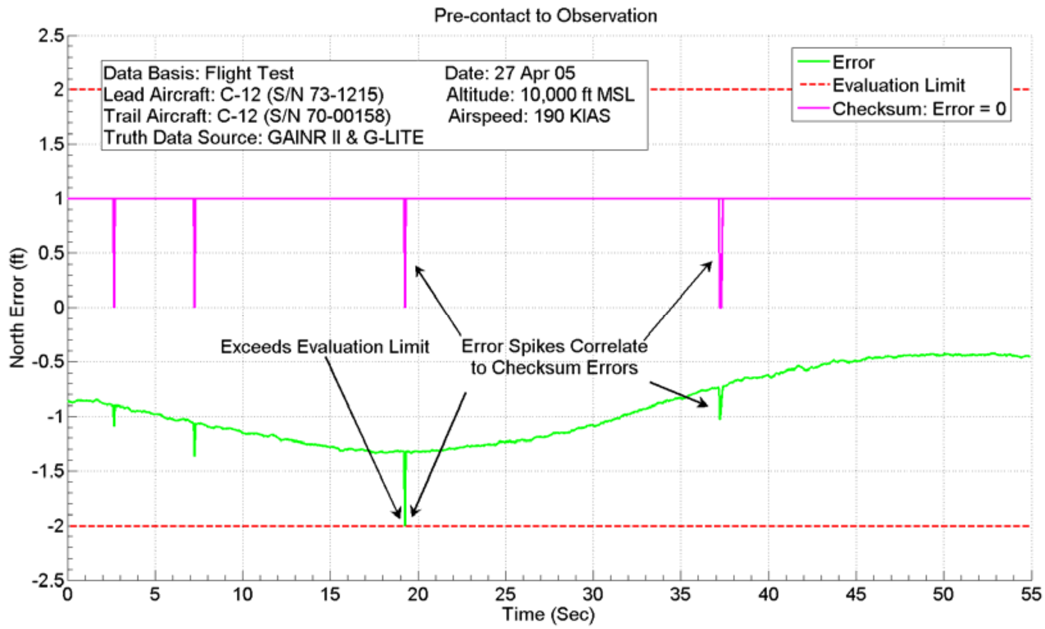

Figure 3: North Error During Pre-contact → Observation Maneuver Corresponding to Checksum Errors

When the trail aircraft had a checksum failure, an updated GPS message from the lead aircraft was not processed and the trail aircraft used a position hold for the position output of the skipped time step. The position hold corresponding to the error at 19 seconds in Figure 3 is illustrated in Figure 4.

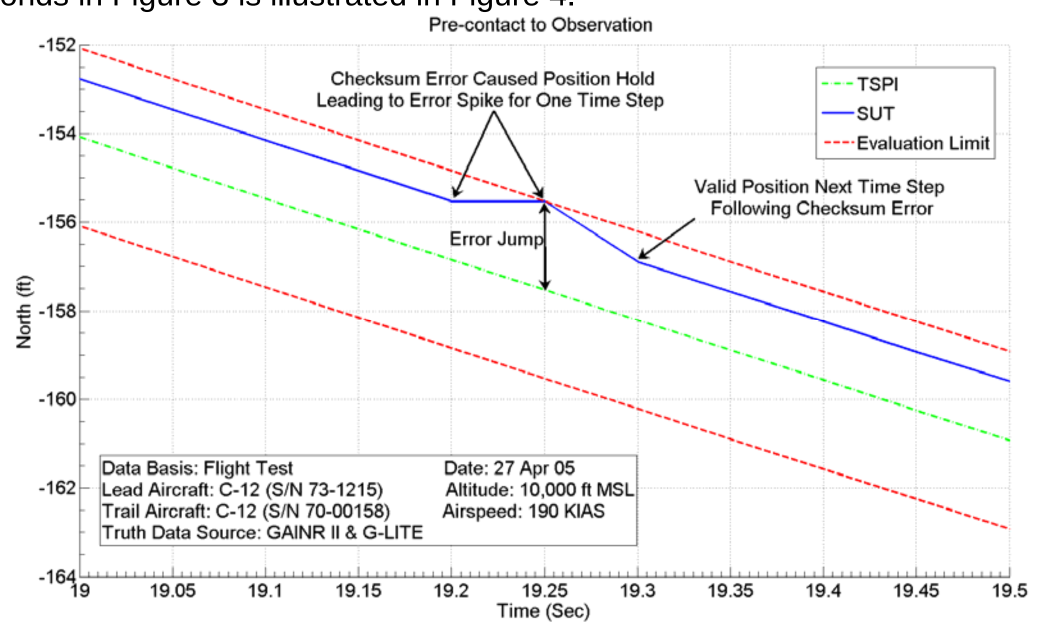

Figure 4: Position Error Caused by Checksum Error

Figure 4 illustrates a fairly constant error for the time leading up to the checksum error, an error jump due to the position hold, and then a constant error following the checksum error. The magnitude of the error jump corresponded to the rate of change of

the parameter of interest, relative North position in this example. Checksum failures that occurred during high rates of change in relative position caused larger errors, as during maneuvering from one position to another. The small error spikes in Figure 3 corresponded to checksum errors during smaller rates of change of relative North position.

Attitude Solution Accuracy

The ability of the SUT to provide an accurate attitude solution was only observed during the test program as no evaluation criteria were established for this objective.

Procedures

The attitude of the lead aircraft was measured by a MEMS IMU with angular drift of the IMU corrected using a Kalman filter with GPS velocity data as an additional input. The attitude data from the lead aircraft were sent to the trail aircraft over the datalink where it was recorded to a data file on the trail aircraft SUT. The following maneuvers were flown to evaluate the attitude solution accuracy of the SUT:

- Straight and Level Unaccelerated Flight (SLUF)
- 2,000 foot Climb and Descent
- Constant 15-Degree Banked Turn for 360 degrees
- Constant 30-Degree Banked Turn for 360 degrees
- 30 Degrees to 30 Degrees Bank to Bank Rolls – ½ Aileron
- Objective 1 Maneuver Set

The all the maneuvers were flown in the data band of 190 ± 5 KIAS and 10,000 ± 100 feet pressure altitude except the climb and decent which were flown at 160 KIAS and 200 KIAS respectively and at a pressure altitude of 8,000 to 10,000 feet. Table B-3 in Appendix B documents these specific maneuvers.

Results

The IMU software had two modes of operation; static and dynamic. While in static mode (i.e., GPS velocity < 10 knots) the IMU relied only on its 3-axis accelerometers for the attitude solution. In dynamic mode (i.e., GPS velocity > 10 knots) the IMU used the GPS velocity vector to update the attitude solution. During ground testing and taxi for the first formation flight, real-time data displays did not indicate any major oscillations in the attitude solution. However, problems with the IMU attitude solution were immediately observed after takeoff indicating a problem with the dynamic mode. The MEMS IMU data oscillated erratically and did not provide an accurate attitude solution while airborne. Figure 5 illustrates the raw IMU data collected during the first formation flight.

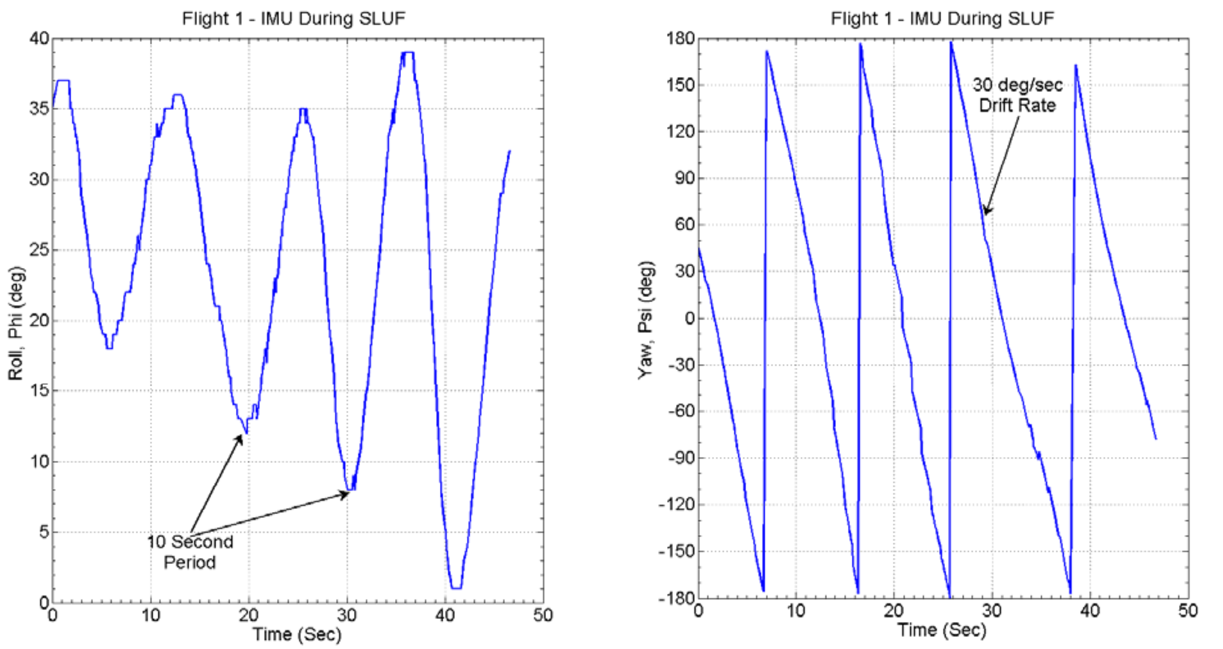

Figure 5: IMU Yaw and Roll Oscillations During First Formation Flight

Between the first and second formation flights, the Kalman filter settings for the IMU were adjusted and a new version of software was loaded for subsequent flights. During the second formation flight the attitude solution was correctly displayed and the observed oscillations were significantly smaller.

The roll, pitch, and yaw accuracies were evaluated by comparing a time history of the attitude data recorded by the system under test with the attitude data recorded by the GAINR on the lead aircraft. A summary of the attitude solution accuracy results for each maneuver is depicted in Table 2. Associated SUT roll, pitch, and yaw data and truth source roll, pitch, and yaw data are displayed in figures D-17 to D-29. These figures show that for straight and level flight the pitch error was a bias of approximately +3 degrees, the roll error was a bias of approximately -3 degrees, and the yaw error was bounded by ±5 degrees until it drifted to -19.8 degrees of error before tracking back to the correct yaw.

Table 2: Summary of SUT Attitude Solution Accuracy

Maneuver	Yaw	Pitch	Roll
	Maximum error in degrees		
SLUF	**-19.80***	4.19	-3.53
Climb	11.50	6.52	-4.11
Observation	-4.14	3.42	-2.80
Pre-contact	**-19.80***	4.19	-3.01
Contact	-2.27	3.43	-2.77
Observation → Pre-contact	-13.70	3.64	-3.53
Pre-contact → Observation	-2.55	3.88	-1.93
Pre-contact → Contact	4.34	3.79	-2.55
Contact → Pre-contact	-1.42	3.54	-2.64
Constant 15°φ Left Turn	-17.80	4.03	**5.52***
Constant 30°φ Right Turn	-15.40	**-7.17***	-4.15
30° to 30° Bank to Bank Rolls – ½ Aileron	-4.32	6.12	0.96
Descent	5.96	-2.73	4.34
**Maximum Yaw, Pitch, and Roll Errors*			

Table 2 illustrates that there are still significant errors in the MEMS IMU accuracies when considering the SUT for use in aerial refueling applications. Table 2 also illustrates that the attitude accuracy was worst in yaw, followed by pitch, and then roll. The attitude errors gradually increased and decreased without sharp increases or decreases. The effect of this error on a trail aircraft using this attitude data to control its position would most likely be an angular displacement of the trail aircraft. Instead of controlling a vehicle to a position directly behind a tanker, it would control it to a lateral position 20 degrees offset from directly behind the tanker. This error would cause significant problems to refueling but would not prevent the system from being usable for follow-on testing with this known limitation. **Continue with follow-on testing using the MEMS IMU but improve MEMS IMU accuracy or replace the IMU with a more accurate attitude sensor for use in autonomous aerial refueling applications. (R1)[1]**

Additional observations were that the SUT output data stream had minor yaw axis oscillations and noise in the roll and pitch axes. The yaw output oscillated at a frequency of 1 Hz and approximately ±0.25 degrees as shown in Figure 6. Oscillations of this magnitude would cause the measured position of the trail aircraft to oscillate laterally by approximately 1 foot at 100 feet relative spacing between the aircraft. This could couple with the lateral directional controller of the trail aircraft and cause difficulties controlling the trail aircraft. A filter could be used to dampen out the oscillatons but would also introduce significant time delay due to the low frequency of the oscillations. In order to prevent the trail aircraft from going unstable in the lateral direction due to this time delay, the system gain would have to be reduced and the trail

[1] Numerals preceded by an R within parentheses at the end of a paragraph correspond to the recommendation numbers tabulated in the Conclusions and Recommendations section of this report.

aircraft would not be as responsive to lateral errors. **Determine the impact of the yaw axis oscillations on the control of the trail aircraft and the feasibility of implementing a filter to reduce the oscillations. (R2)**

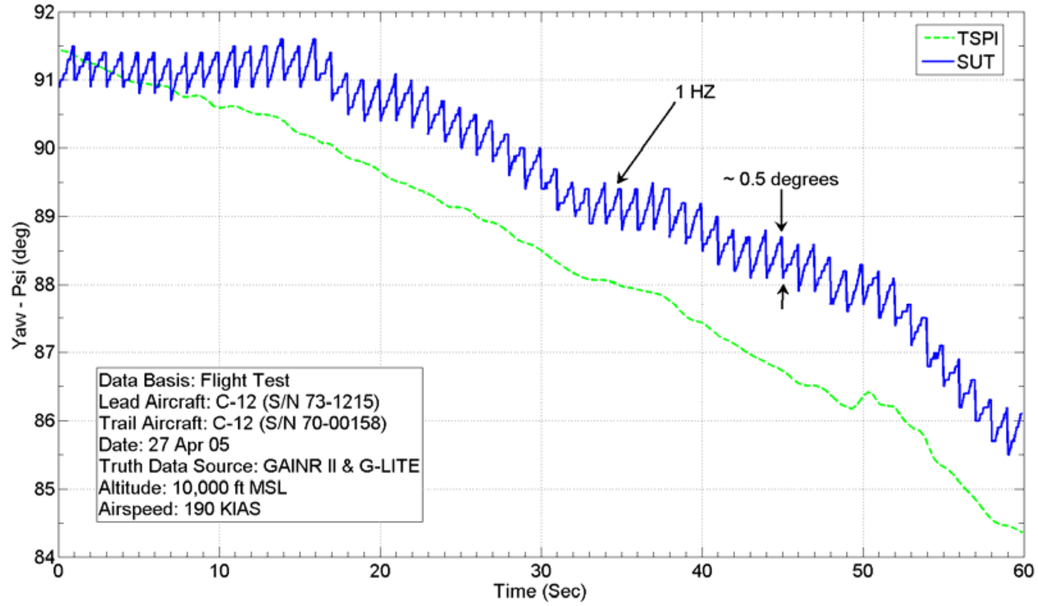

Figure 6: Example of Yaw Output Oscillations

The pitch and roll attitude noise occurred with a magnitude of ±0.1 degrees, but was due to data loss during the quantization of the attitude data into 0.1 degree bins. Figure 7 illustrates noise in the pitch axis observed during SLUF. A plot of the roll axis noise was not included as it had the same characteristics.

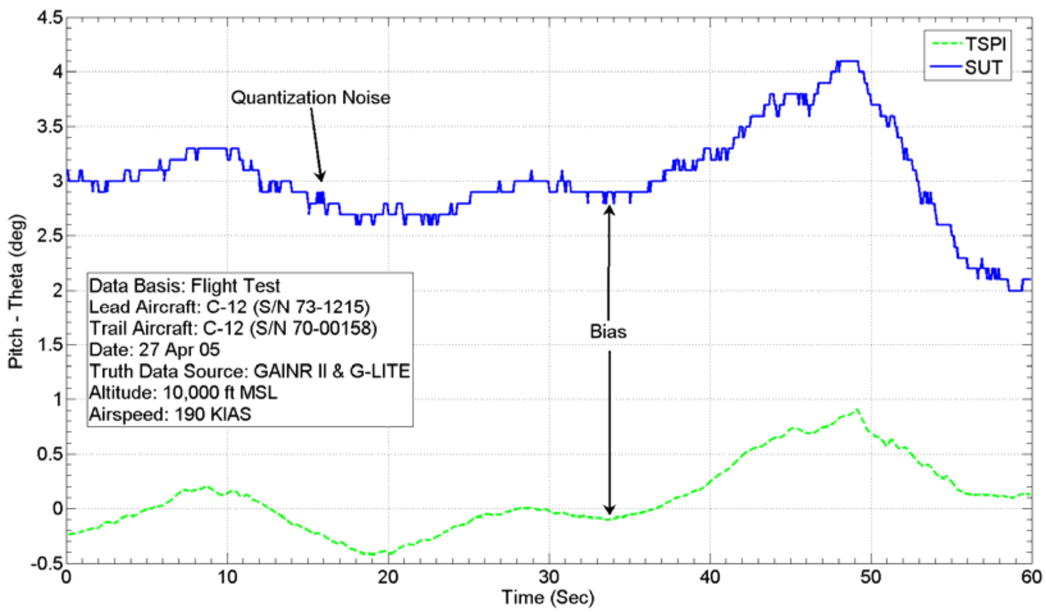

Figure 7: Pitch Output Noise Due to 0.1 Degree Quantization

The noise in pitch and roll due to the 0.1 degree bins could be filtered out with minimal impact to the system.

Datalink Functionality

The test team observed the datalink performance during the flight test and identified factors that may cause degraded performance. The SUT output data stream was analyzed to determine maneuvers that caused checksum failures, datalink dropouts, or other system degradation to occur.

Procedures

The datalink was established prior to takeoff and was set to run for a duration of one hour during testing. The datalink was reestablished in-flight after any system malfunction requiring a SUT restart or after the one-hour data collection period expired. The datalink incorporated a checksum to verify that the data received were the same as the data transmitted from the lead aircraft. When checksum failure occurred, it was recorded on the trail aircraft SUT and the system used a position hold of the previous valid solution for the output. The checksum failures per minute were calculated to indicate which maneuvers caused an increase in checksum failures. Additionally, any SUT anomalies occurring during the entire flight were noted, since the SUT ran during the entire flight.

Results

The number of checksum errors was determined for each specific maneuver performed in Tables B-2 and B-3 of Appendix B. Table 3 below summarizes the datalink checksum errors observed during the flight testing.

Table 3: Summary of SUT Datalink Checksum Errors

Flight Condition	Number of Errors	Average Error Rate (Errors/Minute)
SLUF	42	8.4
Climb	22	5.5
Observation	21	10.5
Pre-contact	9	4.5
Contact	15	7.5
Observation → Pre-contact	13 (11)*	9.8 (12)*
Pre-contact → Observation	7 (9)*	7.7 (12.3)*
Pre-contact → Contact	3 (5)*	2.7 (7.5)*
Contact → Pre-contact	3 (0)*	9.1 (0)*
Constant 15°φ Left Turn	23	3.6
Constant 30°φ Right Turn	6	1.4
30° to 30° Bank to Bank Rolls ½ Aileron	3	6.7
Descent	18	4.5
*(value) for second maneuver flown		

Table 3 indicates that the checksum error rate increased in the observation position averaging over 10 checksum failures per minute as compared to the other maneuvers where it averaged 1.4 to 8.4 checksum failures per minute. The test team theorized that the increase in failure rate could be due to the increased radial distance of this maneuver or due to antennae blocking from the reduced vertical separation during this maneuver. The test team did not have enough data to isolate the cause.

The checksum errors directly led to error in the relative position solution as illustrated in Figure 3 and Figure 4 on page 6. This error was due to the relative position generated by the system remaining a constant value during the checksum error while the truth source value changed. During the checksum failure, the SUT also used the previous valid attitude value as the output. Thus, the checksum failure was equivalent to a time delay of 0.05 seconds for the 20 Hz frequency of the system. **Investigate the primary factors causing an increase in checksum failures and determine the effect of a checksum failure on the autonomous control of a trail aircraft. (R3)**

During the second flight, the SUT provided relative position and attitude information until it stopped functioning due to a problem with the GPS receiver in the lead aircraft. The GPS receiver malfunction on the lead aircraft caused the relative position output to freeze at the last valid solution as illustrated in Figure 8.

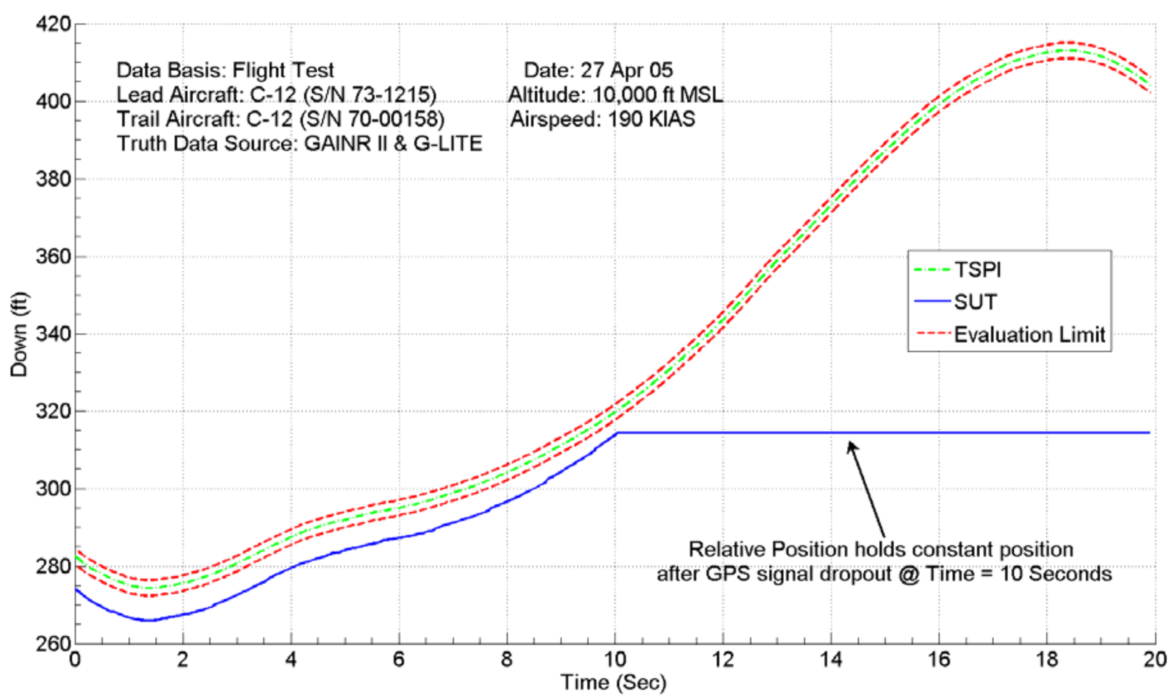

Figure 8: Relative Position Hold due to GPS Receiver Malfunction

The GPS receiver malfunction also led to divergent errors in the attitude data, as GPS velocity vector data was no longer being used as an input to the Kalman filter to correct for IMU drift. Figure 9 shows the roll error beginning to increase following a GPS receiver error at 10 seconds. Because the attitude data were transmitted over the

datalink following the malfunction, the problem was isolated to the lead GPS receiver rather than a problem with the datalink.

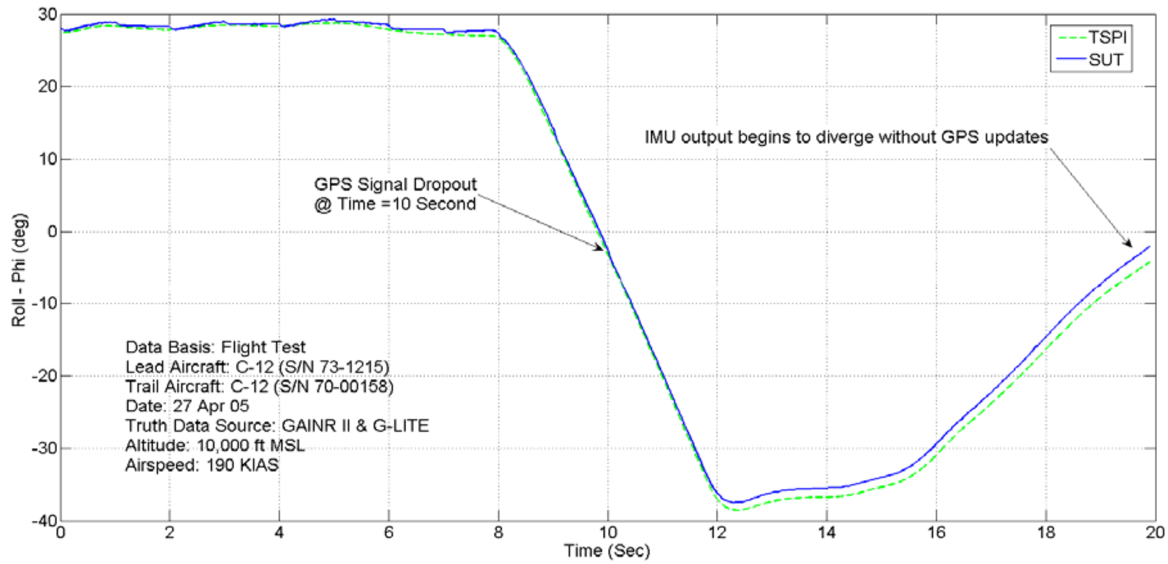

Figure 9: Divergent Attitude Data due to GPS Receiver Malfunction

The system under test on the lead aircraft had to be shutdown and rebooted before resuming testing. Table 4 summarizes the relative position of the trail aircraft and the attitude of the lead aircraft at the time of the GPS receiver problem.

Table 4: Summary of Flight Conditions during GPS Receiver Malfunctions

Position/Maneuver	North (ft)	East (ft)	Down(ft)	Roll (°)	Pitch (°)	Yaw (°)
Trail: Observation Lead: SLUF to 30°	-167	106	-71	-27.5	0.8	52.7
Trail: Observation Lead: SLUF to 30°	-116	-178	-63	-28.2	1.1	129.0
Trail: Safety chase Lead: 30° to 30° ½ Aileron	413	1350	320	-3.2*	1.1	-105.0
Trail: Pre-contact Lead: SLUF to 30°	-96	76	30	27.3	-0.8	-45.6

*Transitioning from a bank angle of -30 degrees to 30 degrees

As this table shows, all of the malfunctions occurred during maneuvers exceeding 25 degrees of bank with little correlation to any other parameter. Bank angle appeared to be the contributing factor to the GPS receiver malfunctions. However, other maneuvers were performed at greater than a 30-degree bank, such as the 360-degree turn at a 30-degree bank in figure D-27 in Appendix D, without causing the GPS receiver to malfunction. The developer theorized that the crashes were due to hardware problems with the GPS receiver card in the SUT, but more testing is required to verify or determine the cause of the malfunction. **Investigate the cause of the GPS data outages on the lead system. (R4)**

This malfunction presents significant safety risks should it occur while using this datalink as a control input for autonomous formation flight of an aircraft. The effect would be to break the closed loop control system without warning to the trail aircraft. **During follow-on testing, utilize a disconnect system to immediately shut off the autopilot and transition to manual control following any unusual/unsafe motion of the trail aircraft. (R5)**

Test and Evaluation Summary

The Lost Wingman SUT performance was not adequate in its tested configuration to support autonomous aerial refueling. However, the system was adequate to support the follow-on Test Management Project (TMP) with proper safety planning and understanding the impact of the system deficiencies on the autonomous flight controller.

During this limited evaluation, the SUT provided accurate relative position data and demonstrated that a low cost MEMS IMU could provide attitude information within ±19.8 degrees of the GAINR Embedded GPS/INS (EGI). Under the time constraints of this test program, only a single iteration of Kalman filter parameter refinement for the MEMS IMU was accomplished. Continued development of the system to include further tuning of the Kalman filter, the use a higher quality IMU, investigation of different INS mechanizations schemes, or the use of higher order state models may provide the needed angular accuracy. GPS receiver malfunctions and checksum errors also interrupted the continuous flow of attitude and position data across the datalink. However, with further maturation, the system had the potential to be used in autonomous aerial refueling applications.

Continue to develop, test, and evaluate the system under test for use in autonomous aerial refueling. (R6)

CONCLUSIONS AND RECOMMENDATIONS

The system under test (SUT) provided accurate relative GPS position solutions within ±2 feet of the GPS Aided Inertial Reference (GAINR) truth source calculated position solution. Two deviations from the ±2 feet requirement were noted, but these deviations would not adversely affect the use of this datalink in controlling a trail aircraft. However, the attitude solution accuracy provided by the Micro-Electrical-Mechanical System Inertial Measurement Unit (MEMS IMU) was erratic and included excessive angular errors. Furthermore, in the current configuration, the datalink had many dropouts and would be unsatisfactory for the purpose of autonomous formation Unmanned Aerial Vehicle operations. However, the system has the potential to provide relative position and attitude information for use in autonomous aerial refueling.

Continue to develop, test, and evaluate the system under test for use in autonomous aerial refueling. (R6, page 14).

The following conclusions and recommendations are prioritized in terms of safety of flight and impact to follow-on testing. Deficiencies in the datalink have the potential to disrupt follow-on testing which use the datalink to control a trail aircraft. In order to safely conduct follow-on testing with this deficiency, the operators of the trail aircraft should employ autopilot disconnect devices**.**

During follow-on testing, utilize a disconnect system to immediately shut off the autopilot and transition to manual control following any unusual/unsafe motion of the trail aircraft. (R5, page 14)

The primary deficiency identified during testing was a GPS receiver malfunction on the lead system which caused a freeze in the relative position data and caused the attitude data to diverge. The cause of the malfunction was not confirmed during the testing but all four of the malfunctions occurred during maneuvering at greater than 25 degrees of bank by the lead aircraft.

Investigate the cause of the GPS data outages on the lead system. (R4, page 13)

Two deficiencies were noted with the attitude output from the system under test. First, the yaw output had a noise signal of ±0.25 degrees oscillating at 1 Hz due to the algorithm using GPS velocity vector to correct for IMU drift. This oscillation could adversely impact the control system of the trail aircraft during follow-on testing.

Determine the impact of the yaw axis oscillations on the control of the trail aircraft and the feasibility of implementing a filter to reduce the oscillations. (R2, pages 9-10)

Additionally, attitude accuracy of the system was not sufficient for autonomous aerial refueling as errors up to 19.8 degrees in yaw were observed. This error would manifest itself as an angular displacement of the trail aircraft. This error would adversely effect autonomous aerial refueling where the trail aircraft must be directly behind the tanker. However, this error would not prevent flight testing of the control laws on the trail aircraft as flying directly behind the lead aircraft would not be a requirement for the testing.

Continue with follow-on testing using the MEMS IMU but improve MEMS IMU accuracy or replace the IMU with a more accurate attitude sensor for use in autonomous aerial refueling applications. (R1, page 9)

Finally, there were interruptions in the datalink transmissions/receptions, manifested as checksum errors at a rate of up to 12.3 errors/minute. The impact on controlling a trail aircraft was expected to be equivalent to a time delay of one time step of 0.05 seconds for the 20 Hz frequency of the system.

Investigate the primary factors causing an increase in checksum failures and determine the effect of a checksum failure on the autonomous control of a trail aircraft. (R3, page 12)

This test program demonstrated that a low cost GPS and MEMS IMU with a datalink could provide relative position and attitude information between an aircraft formation. The system had deficiencies in datalink functionality, attitude accuracy, and noise that must be overcome prior to future use in autonomous aircraft applications. However, the system demonstrated potential for use during autonomous aerial refueling with improved performance and reliability and was capable of supporting follow-on testing with limitations due to the observed deficiencies.

REFERENCES

1. Flight Manual, USAF Series Aircraft, C-12C, Technical Order 1C-12A-1, HEBCO, Inc., 1 November 2003.

2. Taschner, Michael J., Lieutenant Colonel, USAF, *Modification Flight Manual: C-12C, Serial Number 73-1215*, Air Force Flight Test Center, Edwards AFB CA, 23 September 2002.

3. Peters, Patrick J. *Modification Operational Supplement: C-12C, Serial Number 73-1215*, Department of Defense, Edwards AFB CA, 21 March 2005.

4. Peters, Patrick J. *Modification Operational Supplement: C-12C, Serial Number 76-0158*, Department of Defense, Edwards AFB CA, 21 March 2005.

5. Embedded GPS INS TSPI System (EGITS) Validation/Verification, F33657-96-D-2006, Aeronautical System Center, Wright-Patterson AFB, Ohio, June 1997

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APPENDIX A – DETAILED TEST ARTICLE DESCRIPTION

The system under test (SUT) consisted of a datalink antenna, datalink transceiver, GPS receiver, Micro-Electro-Mechanical System Inertial Measurement Unit (MEMS IMU), and datalink computer and software on the lead aircraft. A datalink antenna, datalink transceiver, GPS receiver, and datalink computer and software completed the SUT on the trail aircraft. GPS and attitude information from the lead aircraft were passed through the datalink to the trail aircraft. The datalink transmitter transmitted at one Watt over the omni-directional datalink antenna at a frequency of 902 MHz to 928 MHz and at a 20 Hz data rate. The SUT GPS receivers were spliced into GPS antennae mounted on the tails of both C-12s. The customer-supplied GPS antenna was not used during flight testing. The test unit in the lead aircraft received the raw GPS data from the GPS antenna/receiver and the attitude information from the MEMS IMU. It then transmitted this data through the datalink antenna to the test unit in the trail aircraft. The trail test item received the datalink signal from the lead aircraft and calculated the relative position of the trail aircraft and stored the MEMS IMU data.

Specialized software was designed and loaded onto the datalink computer to collect information from the GPS receiver, datalink transceiver, and MEMS IMU, and to determine the relative position and attitude solution.

The IMU software had two modes of operation: static and dynamic. While in static mode (i.e., GPS velocity < 10 knots) the IMU relied only on its 3-axis accelerometers for its attitude solution. In dynamic mode (i.e., GPS velocity > 10 knots) the IMU used the GPS velocity vector to update the attitude solution.

The SUT had an embedded personal computer in a modified PC/104 form factor called Athena. The embedded personal computer had a Linux operating system. Table A-1 documents the SUT components used during the Lost Wingman Test Management Project. Figure A-1 illustrates the SUT as installed on the aircraft. Figure A-2 illustrates the external datalink antenna installation location on C-12C tail #73-1215.

Table A-1: Lost Wingman TMP SUT Components

Component	Model	Manufacturer
Datalink Transceiver	PCFW-104 OEM	Microbee Systems, Inc
DC Power Supply	HE104MAN-V8	Tri-M Engineering
Embedded Personal Computer	ATH-400 Athena	Diamond Systems, Inc
GPS Receiver Card	JNS100 OEM	Javad Navigation Systems
GPS Antenna	P1 Active Antenna	Laipac Technology, Inc
MEMS IMU	MT9 Inertial Motion Tracker	Xsens Technologies, B.V.
UHF Datalink Antenna	P/N 6008	Haigh-Farr
Ethernet Crossover Cable	Generic	Generic
Interface Laptop	Latitude with dual operating systems: Linux/Windows XP	Dell, Inc

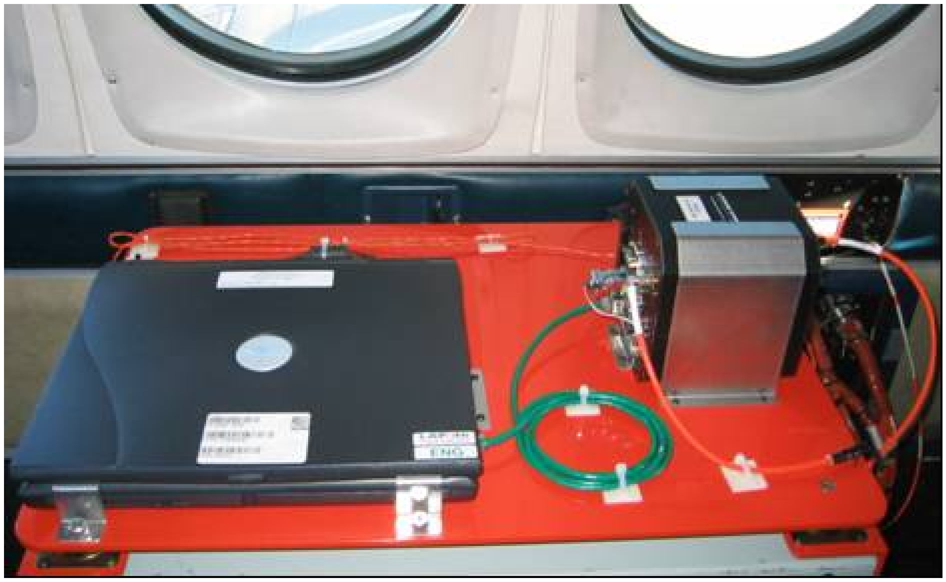


Figure A-1: C-12C Tail # 73-1215 Test Hardware

Figure A-2: C-12C Tail # 73-1215 Datalink Antenna

Two C-12C Huron test aircraft, tails # 73-1215 and #70-00158, were used to collect data for this test program. The C-12C was a Raytheon King Air twin-engine turboprop transport aircraft. A detailed description of the C-12C was found in the C-12C Flight Manual (Reference 1). Detailed descriptions of aircraft modifications were found in the Modification Flight Manual (MFM) (Reference 2) and Modification Operational Supplements (MOS) (Reference 3 and 4).

The test support hardware consisted of two truth sources supplied by 412th Test Wing, Range Support Division Edwards AFB (412 TW/ENR). A GPS Aided Inertial Reference (GAINR) system was the truth source on C-12C #73-1215 and a GAINR-Lite system (i.e., no Embedded GPS INS) was the truth source on C-12C #70-00158. According to Reference 5, the GAINR-II accuracy was identified at 1 foot accuracy. With two GAINR sources used for truth source relative GPS solution, the accuracy was 2 feet. Figure A-3 illustrates the three components of the GAINR system and figure A-4 illustrates the GAINR-Lite system used during the test program.

Figure A-3: Components of the GPS Aided Inertial Reference System

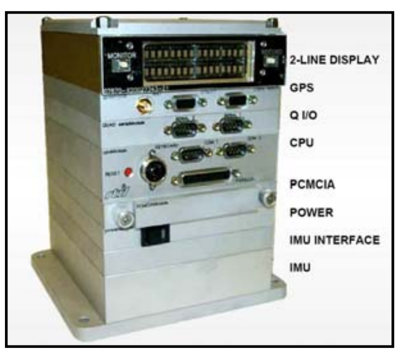
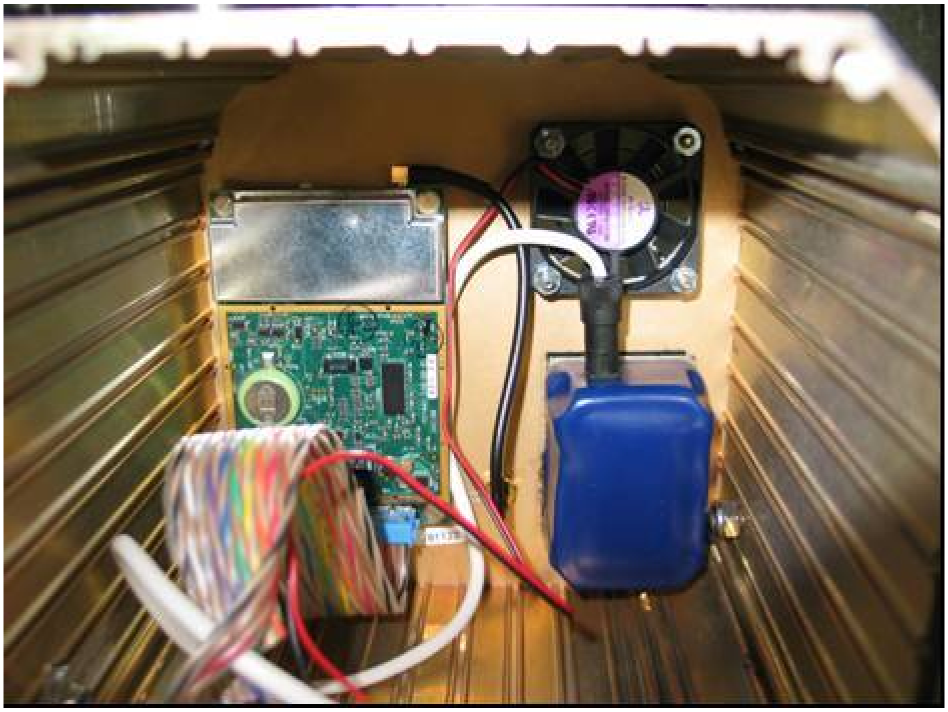


Figure A-4: GPS Aided Inertial Reference System – Lite



Javad GPS Receiver Card (left) and MEMS IMU (lower right) mounted inside Lost Wingman SUT

APPENDIX B – MANEUVER SETS

Table B-1: Lost Wingman Test Summary

Date	Sortie #	Sortie Duration(hrs)	Tasks Completed
18 April 05	1,2	2.3/2.2	Relative GPS Position Maneuver Set
27 April 05	3,4	2.2/2.2	Relative GPS Position Solution and Attitude Solution Maneuver Set

Table B-2: C-12C Aircraft Maneuver Set For SUT Relative GPS Position Solution Testing

Trail Position	Nominal Conditions	Remarks
Pre-contact*	190 KIAS, 10,000 ft PA	TOL: ±5 kts, ±100 ft
Contact*	190 KIAS, 10,000 ft PA	TOL: ±5 kts, ±100 ft
Observation*	190 KIAS, 10,000 ft PA	TOL: ±5 kts, ±100 ft
Pre-contact to Contact	190 KIAS, 10,000 ft PA	TOL: ±5 kts, ±100 ft
Contact to Pre-contact	190 KIAS, 10,000 ft PA	TOL: ±5 kts, ±100 ft
Observation to Pre-contact	190 KIAS, 10,000 ft PA	TOL: ±5 kts, ±100 ft
Pre-contact to Observation	190 KIAS, 10,000 ft PA	TOL: ±5 kts, ±100 ft

* NOTE: Stabilized Maneuvers

Table B-3: C-12C Aircraft Maneuver Set For SUT Attitude Solution Testing

Maneuver	Nominal Conditions	Remarks
Climbs	160 KIAS, 8-10K ft PA	Δ Alt of at least 2000 ft PA
Straight and Level Unaccelerated Flight*	190 KIAS, 10,000 ft PA	TOL: ±5 kts, ±100 ft
Constant G Turns*	190 KIAS, 10,000 ft PA	Data band 5°- 30° of bank TOL: ± 5° AOB, ±200 ft, ±5 kts
30° to 30° Bank-to-Bank Rolls – ½ Deflection	190 KIAS, 10,000 ft PA	TOL: ±1000 ft
Descents	200 KIAS, 10-8K ft PA	Δ Alt of at least 2000 ft PA

* NOTE: Stabilized Maneuvers

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APPENDIX C – C-12C FORMATION FLYING POSITIONS

Pre-contact: Based on experiences drawn from refueling behind a KC-10 and KC-135 in other aircraft, the appropriate visual references were established for the pre-contact position. The trail aircraft was at 30-degree elevation below the lead aircraft's flight path with approximately 80 feet separation. To initially aid with the proposed pre-contact position references, the 30-degree elevation was designated using tape and the underbelly VHF antenna just behind the nose gear doors of the C-12 as illustrated in figure C-1.

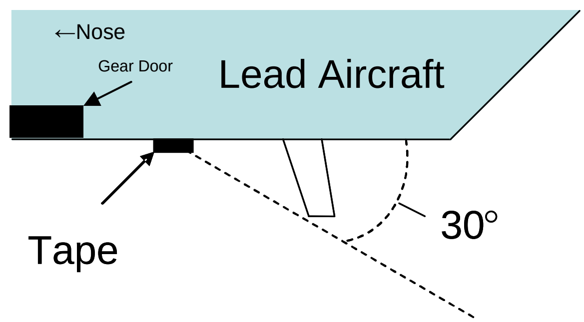

Figure C-1: Trail aircraft elevation reference

Flying the taped position references yielded a position that according to instructor experience was too low for a pre-contact position. Actual references used while flying the pre-contact position were the horizontal stabilizer and tail in the upper part of the windscreen and the tip of the VHF antenna mentioned above on the gear doors versus the tape. The two black rock guards protecting the beacon were lined up on the two ADF blister antennas. Another reference used was the wing leading edge splitting the exhaust pipes. These actual references established the 30-degree elevation line. Keeping these references the aircraft was then flown into the contact position.

Contact: The trail aircraft was at a 30-degree elevation below the lead aircraft's flight path with approximately 50 feet separation from the antenna reference to the trail aircraft cockpit. Approximately 10 feet nose/tail separation was maintained and the trail aircraft tail was below the lead aircraft as is illustrated in figure C-2.

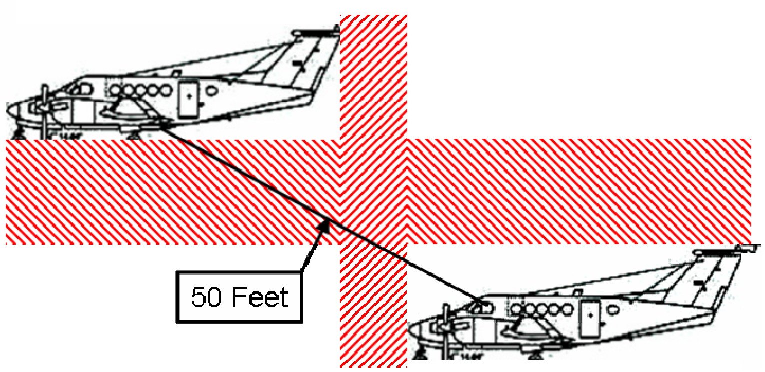

Figure C-2: Pre-contact Position

Observation: The trail aircraft was at an altitude no lower than level with the lead aircraft. The trail aircraft was line abreast to 10 degrees aft of line abreast with approximately 50 feet wingtip spacing. For this test, the trail aircraft was in position on the right side of the lead to give the pilot flying the best view of the lead aircraft. The visual references were determined by lining up the two pilots in the lead aircraft and visualizing another C-12 between the two aircraft. With a wingspan of 54 feet 6 inches, 50 feet of wingtip spacing was judged by doubling the approximately 25 right wing of the lead aircraft and verifying that spacing existed between the two wingtips.

Pre-contact to Contact: While maintaining the 30-degree elevation line, the trail pilot closed towards the contact position at a rate not to exceed 1 foot/second and maintaining positive nose-tail separation.

Contact to Pre-contact: While maintaining the 30-degree elevation line, the trail pilot extended from the contact position of 50 feet with a rate not to exceed 1 foot/second and stabilized in the pre-contact position.

Observation to Pre-contact: The trail aircraft first maneuvered aft to ensure nose tail separation of approximately 100 feet and then descended to establish the trail aircraft on the 30-degree elevation line using the tape described in the Pre-contact section as a visual reference. Once established on the 30-degree elevation line, the pilot maneuvered laterally to place the aircraft directly behind the lead aircraft. The pilot would then move forward to the pre-contact position using the visual reference marks described in the pre-contact section and stabilize with a zero-rate of closure.

Pre-contact to Observation: First, the trail aircraft moved aft to ensure nose tail separation of approximately 100 feet. Once proper nose tail separation had been achieved, the trail pilot moved laterally to establish 50 feet wingtip separation. Next, the trail aircraft climbed to an altitude level with the lead aircraft and moved forward to stabilize in the observation position with a zero rate of closure.

Straight Level Unaccelerated Flight (SLUF): The lead aircraft was trimmed on test conditions within the data band. Autopilot was used to maintain heading and altitude.

Constant Bank Turns: The lead aircraft stabilized in a level 15-degree or 30-degree bank turn. Once stabilized, the pilot maintained the bank and altitude through 360 degrees of heading change in one continuous maneuver.

30 Degrees to 30 Degrees Bank-to-Bank Turn – ½ Aileron: The aircraft was stabilized in a 30-degree bank turn to the left or right. When stable, a ½ deflection aileron input to reverse the turn direction was abruptly applied. The aileron input after rolling through 30 degrees of bank in the opposite direction was then removed.

Climb: The aircraft were stabilized in a climb at 160 KIAS with 1900 Propeller RPM (PRPM) and climb power set. Data were recorded through at least 2000 feet of altitude.

Descent: The aircraft were stabilized in a 1000 fpm descent at 200 KIAS with 1700 PRMP set. Data were recorded through at least 2000 feet of altitude.

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APPENDIX D – FIGURES

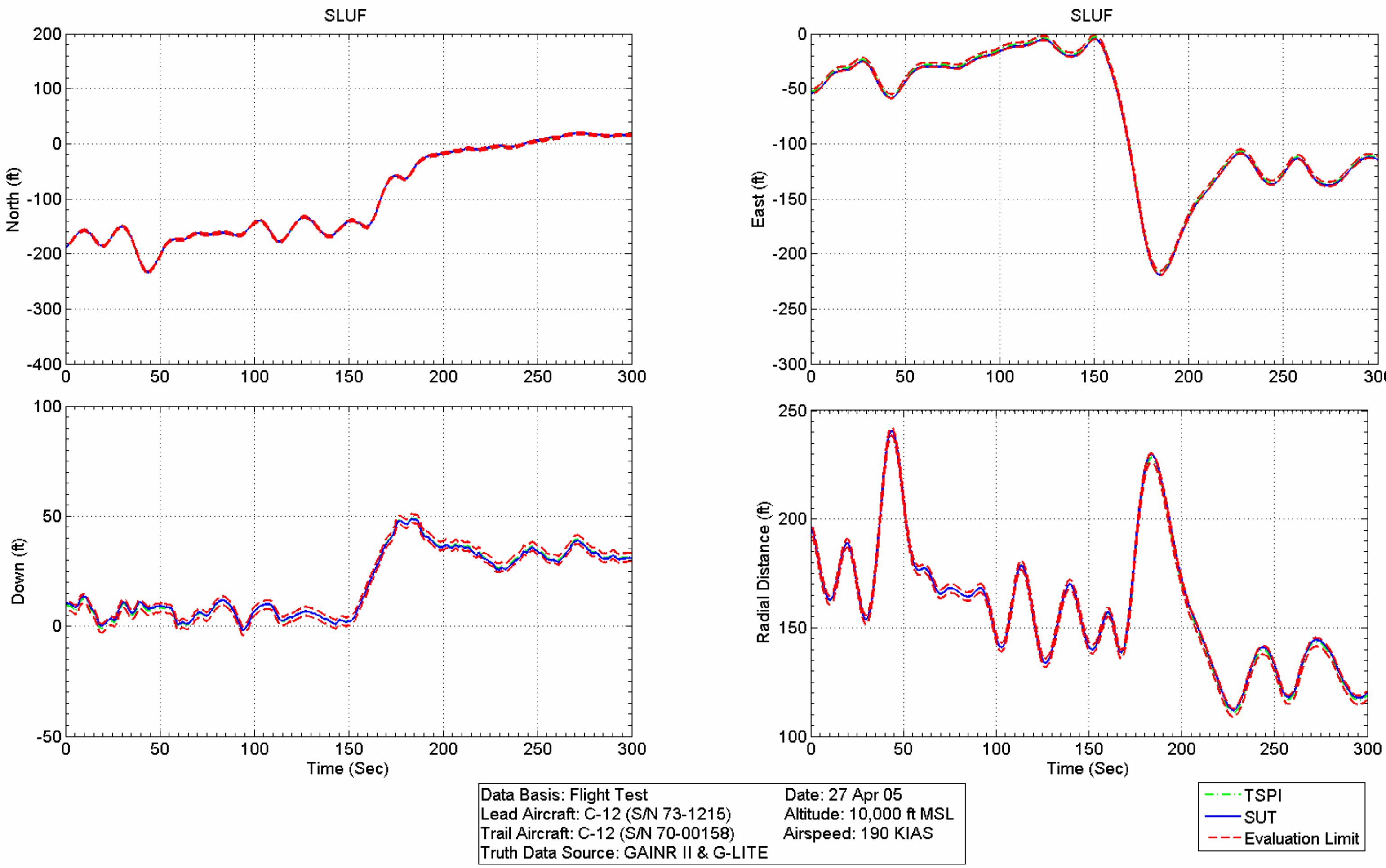

Figure D-1: Relative GPS Position Comparison between System Under Test (SUT) and truth source in Straight & Level Unaccelerated Flight (SLUF)

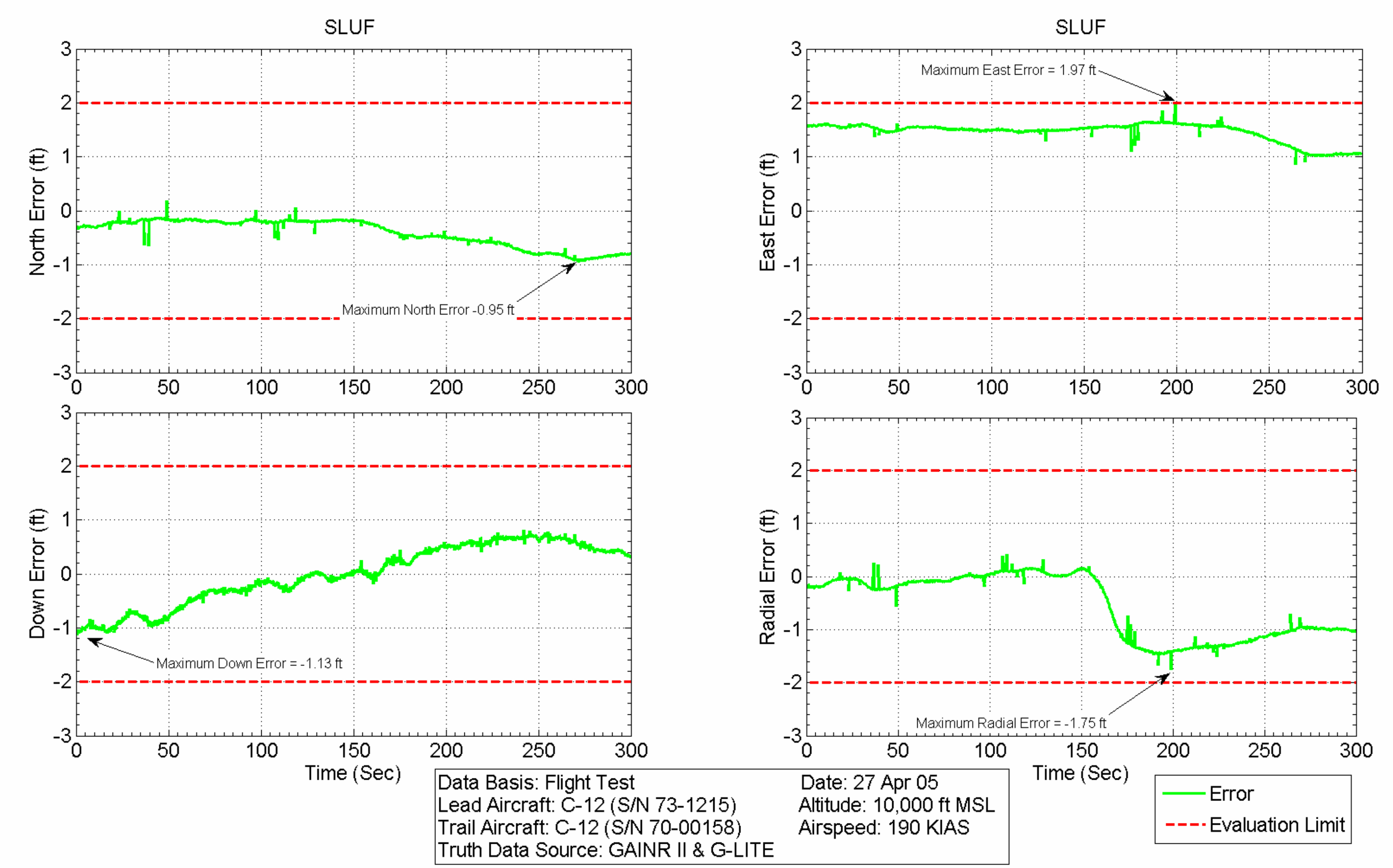

Figure D-2: Relative GPS Position Error in SLUF

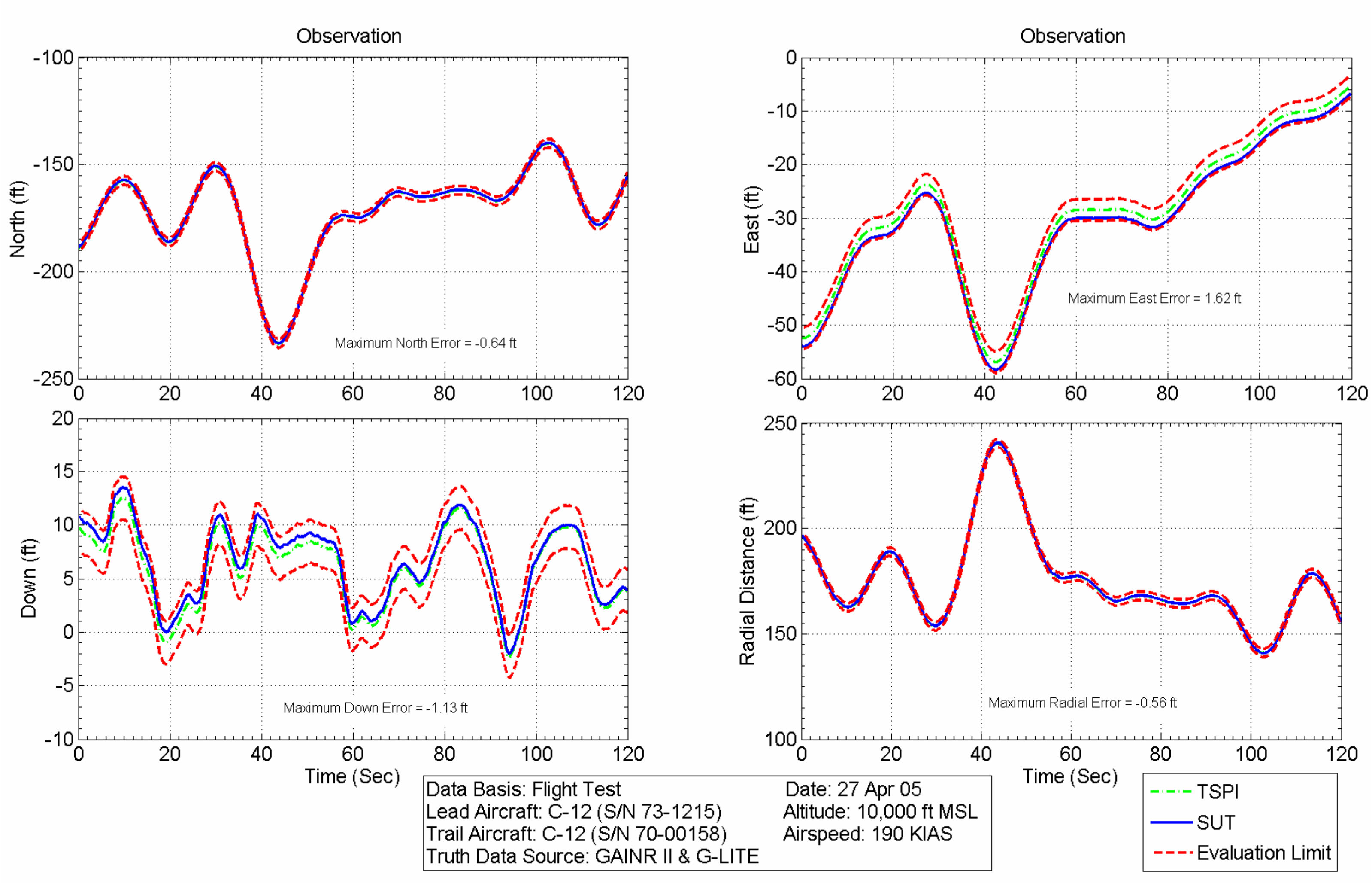

Figure D-3: Relative GPS Position Comparison between SUT and truth source in the Observation Position

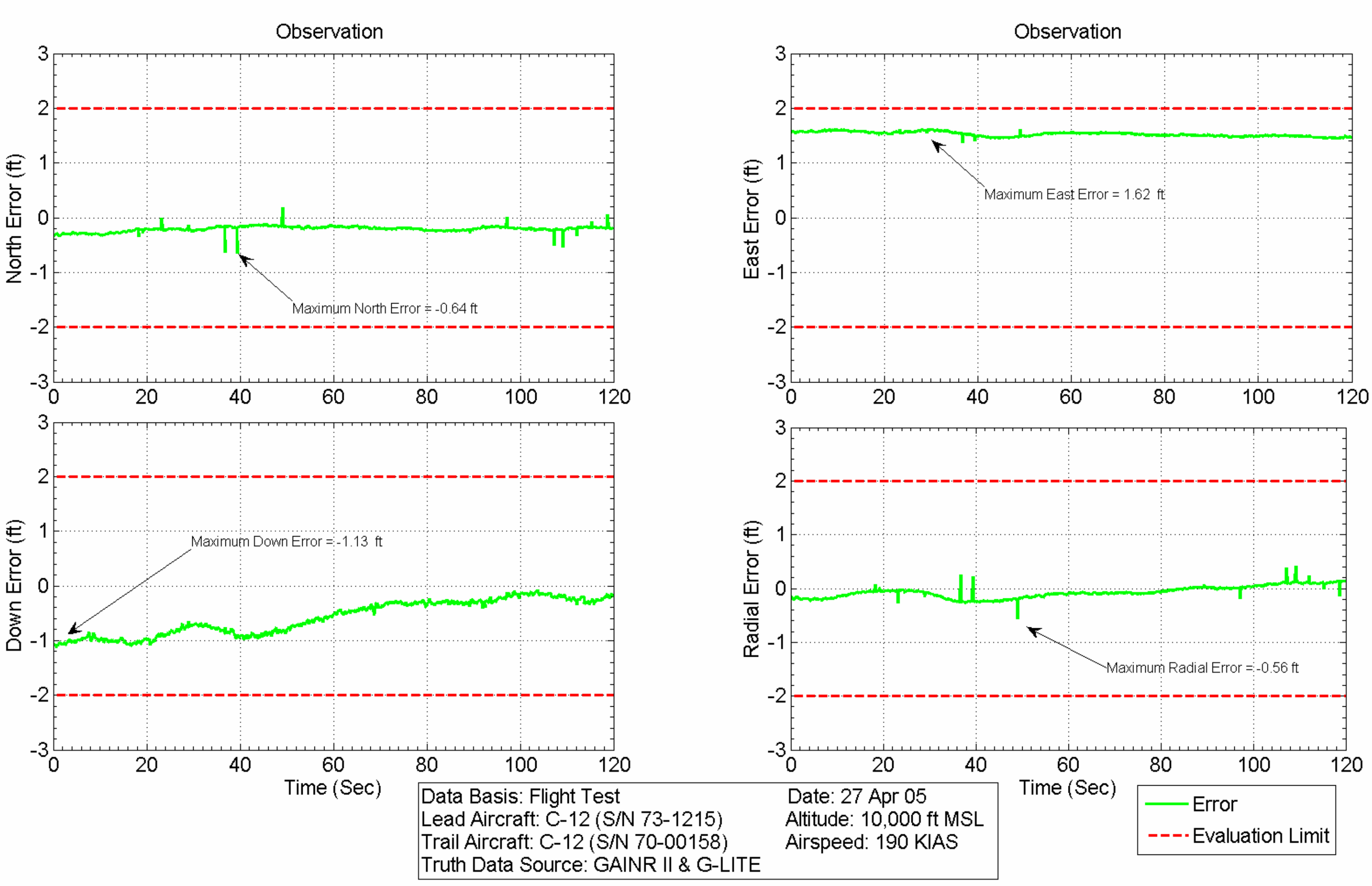

Figure D-4: Relative GPS Position Error in the Observation Position

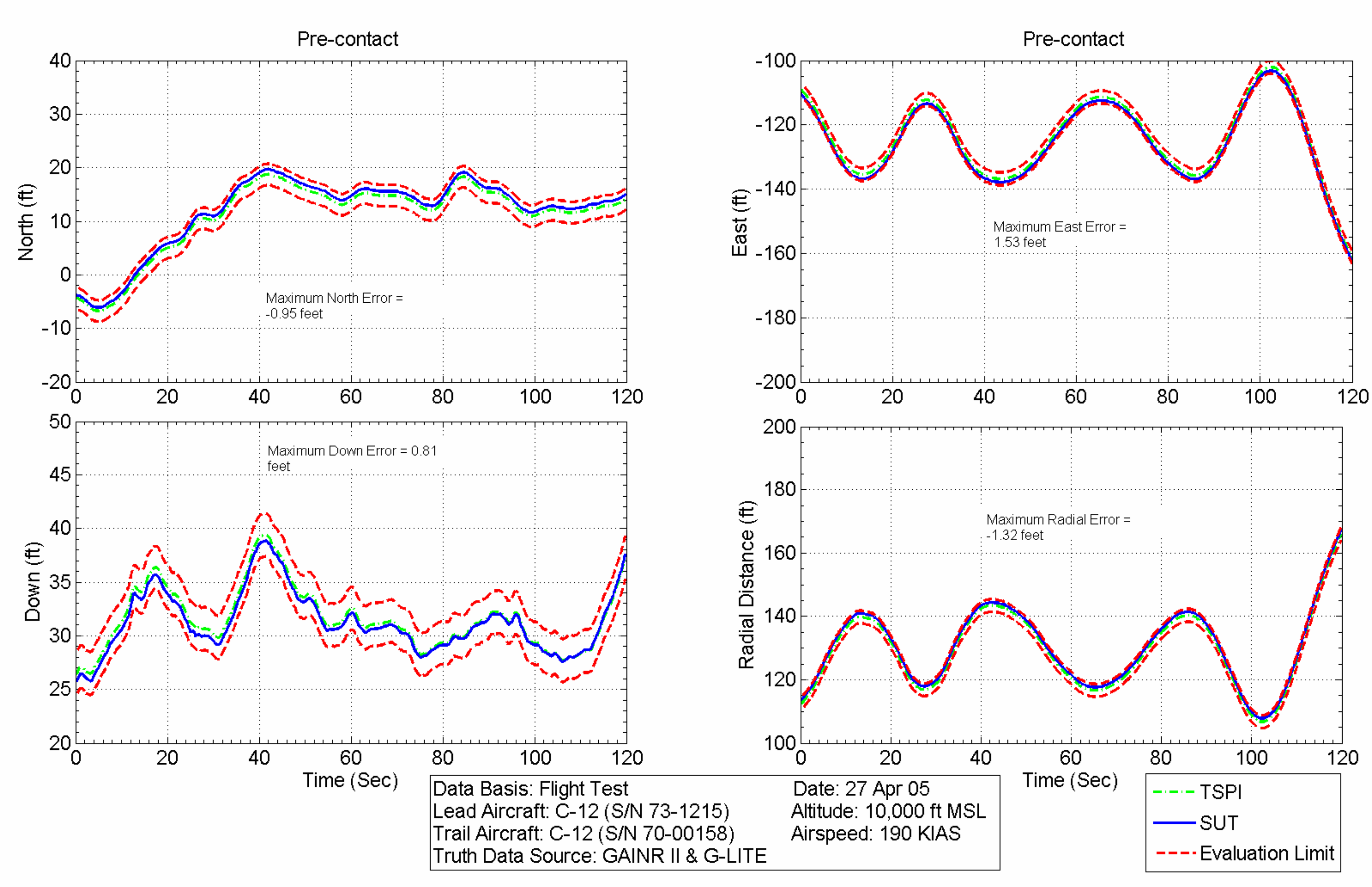

Figure D-5: Relative GPS Position Comparison between SUT and truth source in the Pre-contact Position

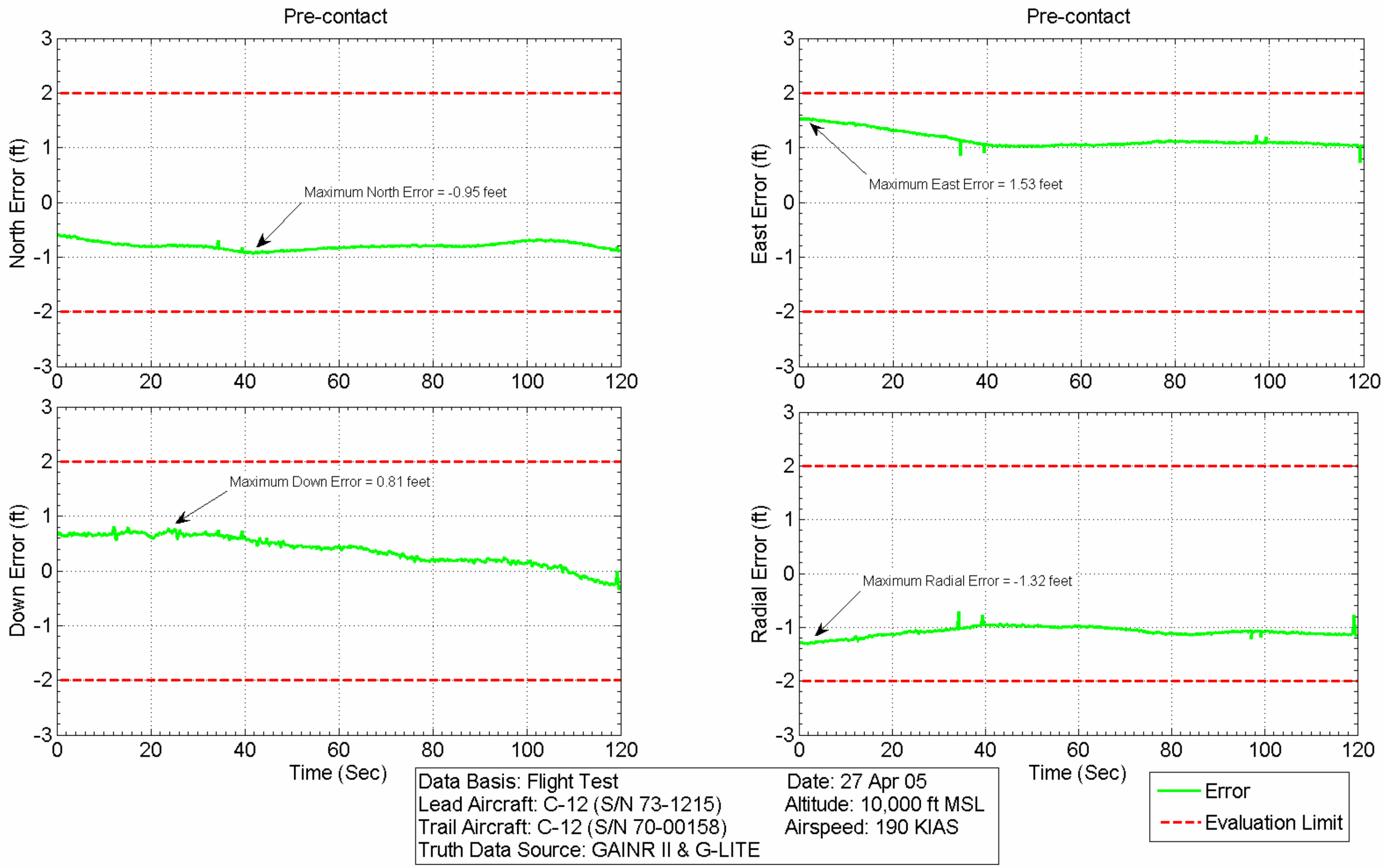

Figure D-6: Relative GPS Position Error in the Pre-contact Position

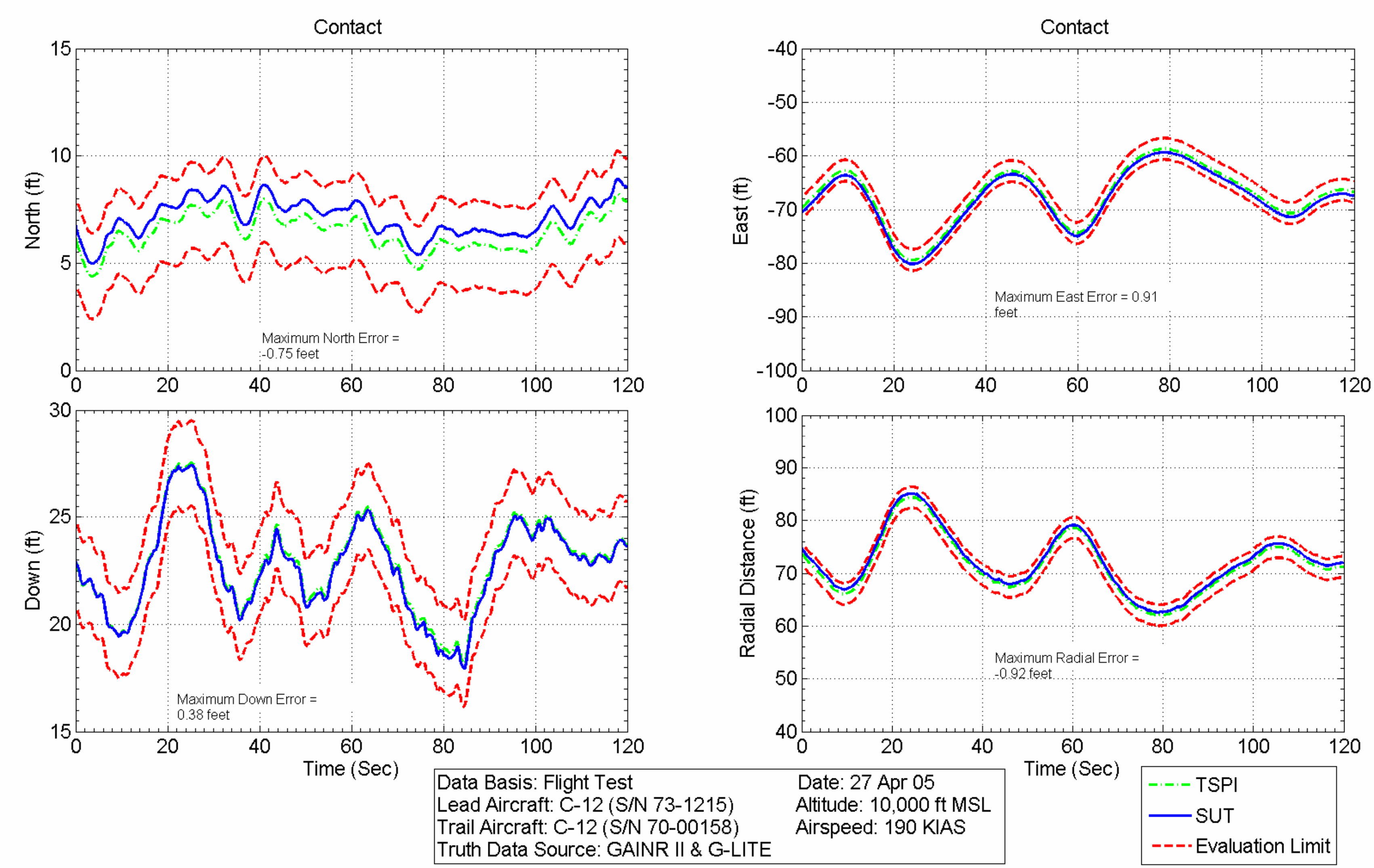

Figure D-7: Relative GPS Position Comparison between SUT and truth source in the Contact Position

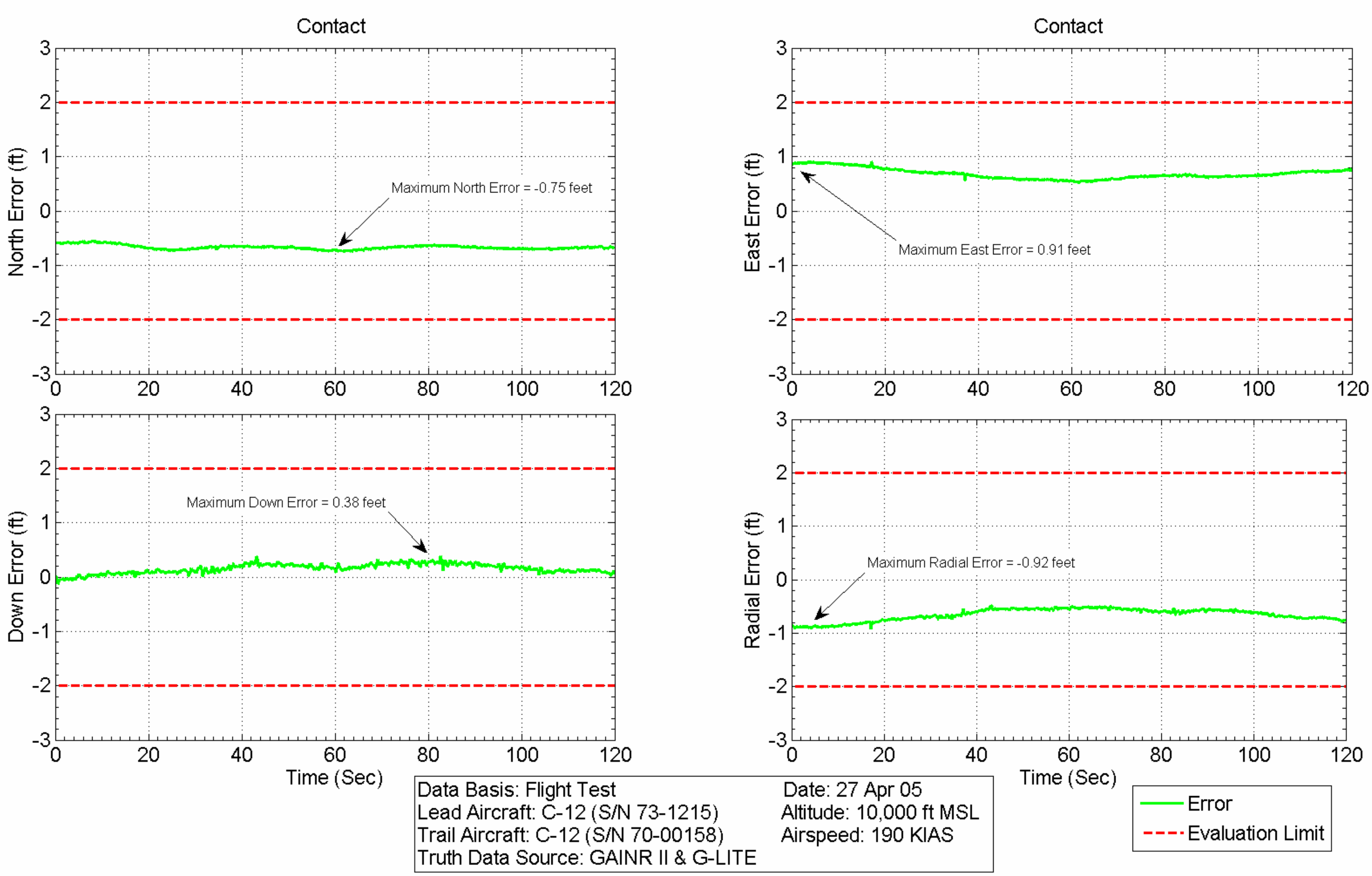

Figure D-8: Relative GPS Position Error in the Contact Position

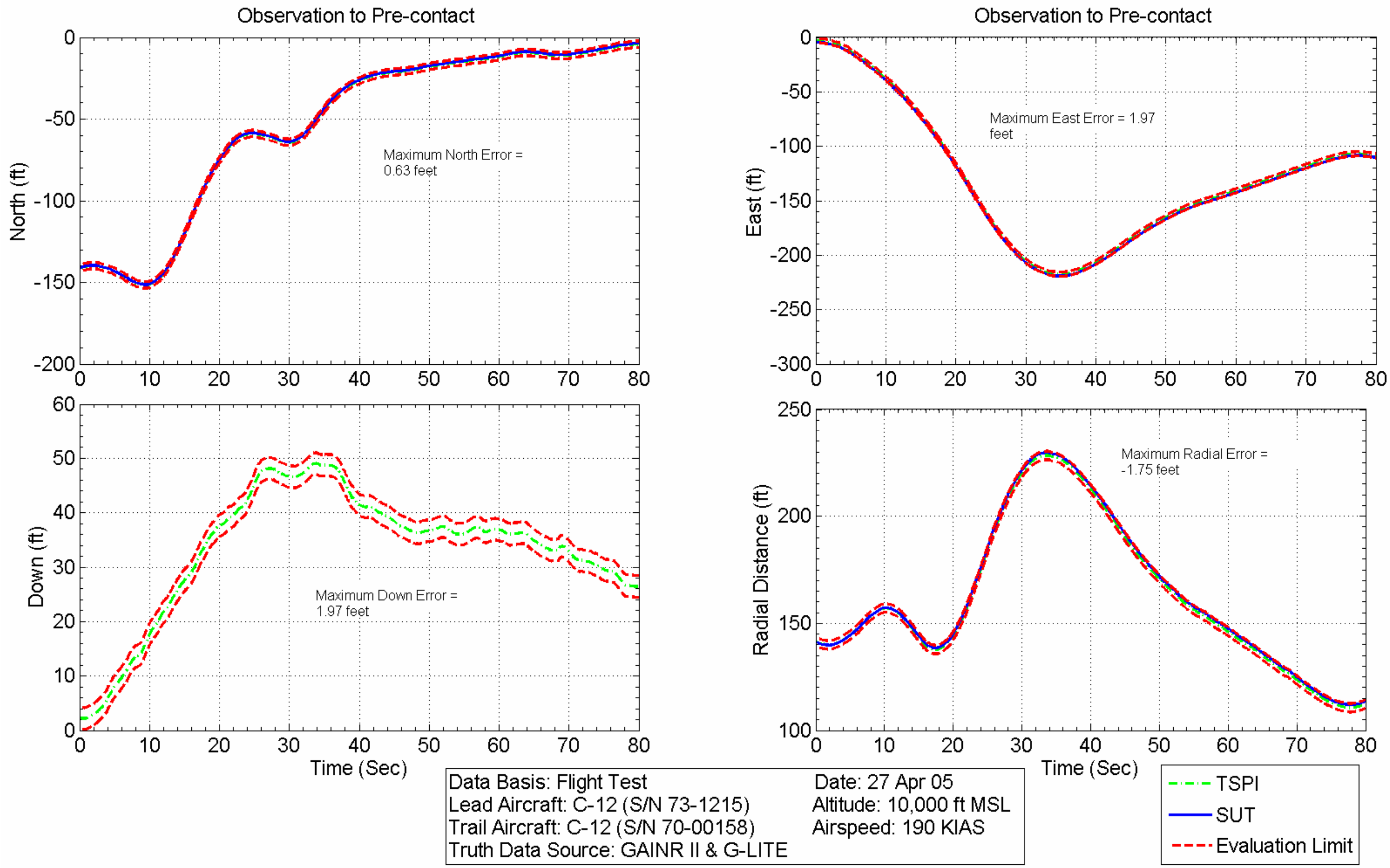

Figure D-9: Relative GPS Position Comparison between SUT and truth source during the Observation Position to Pre-contact Position transition

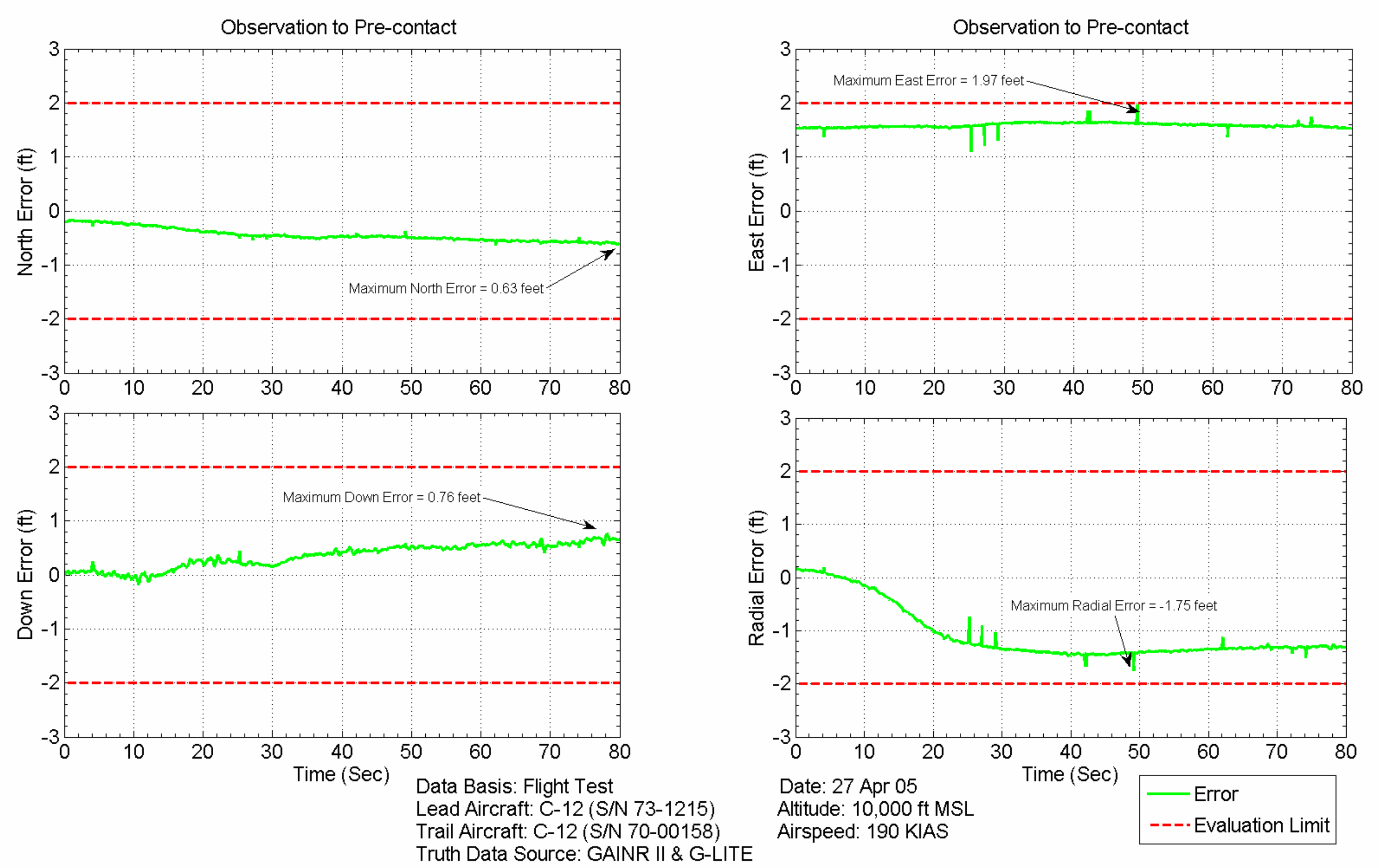

Figure D-10: Relative GPS Position Error during the Observation Position to Pre-contact Position transition

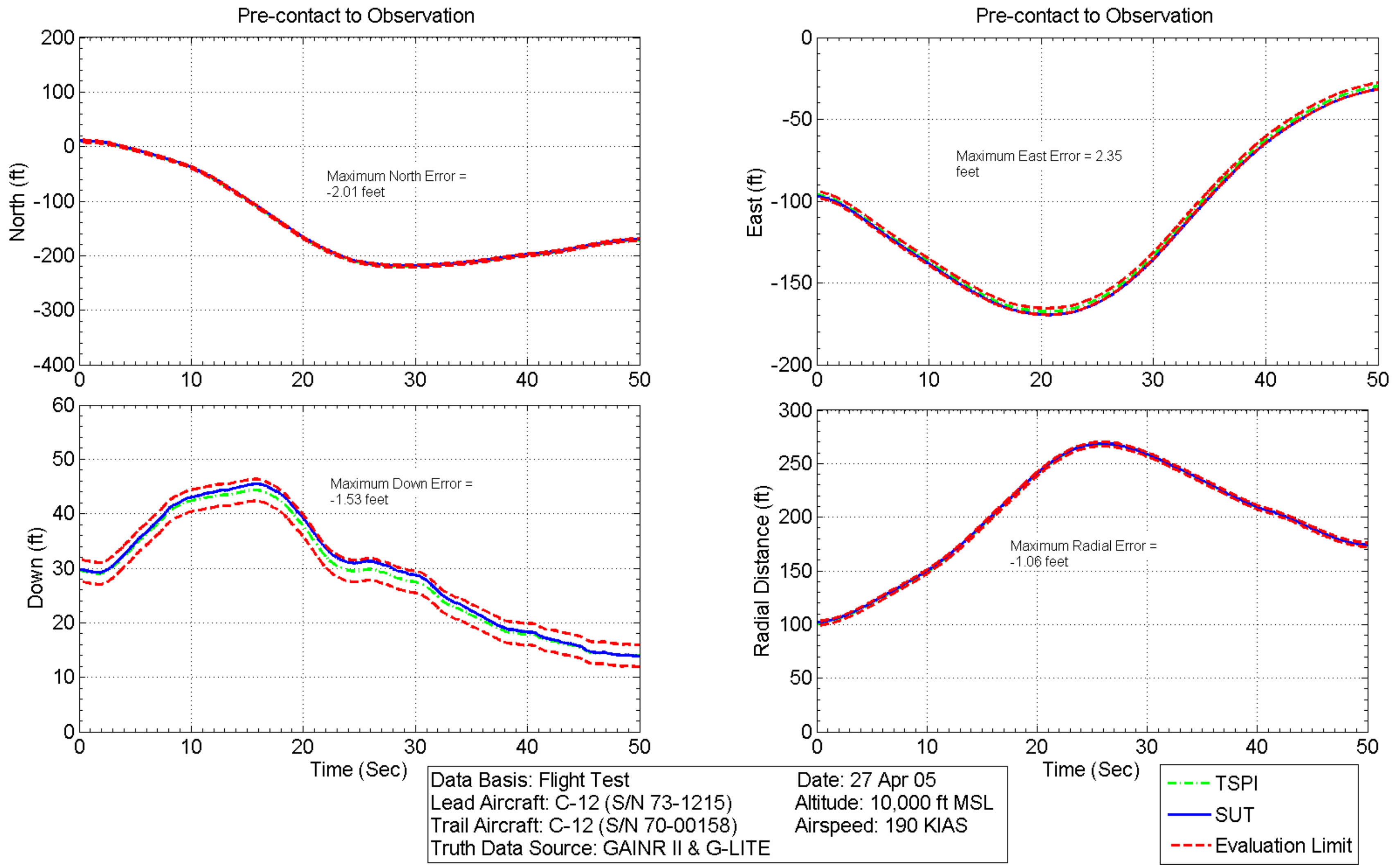

Figure D-11: Relative GPS Position Comparison between SUT and truth source during the Pre-contact Position to Observation Position transition

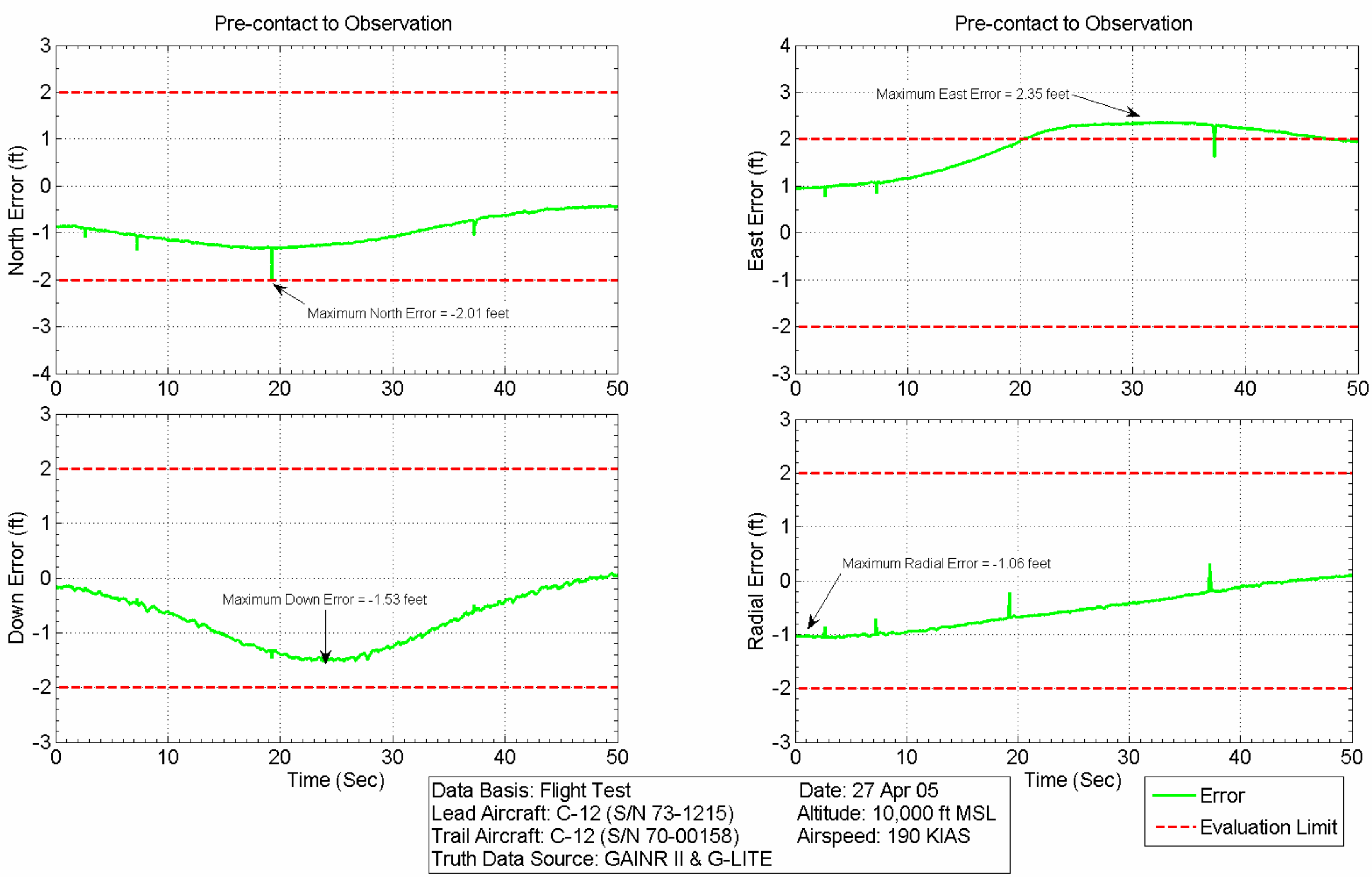

Figure D-12: Relative GPS Position Error during the Pre-contact Position to Observation Position transition

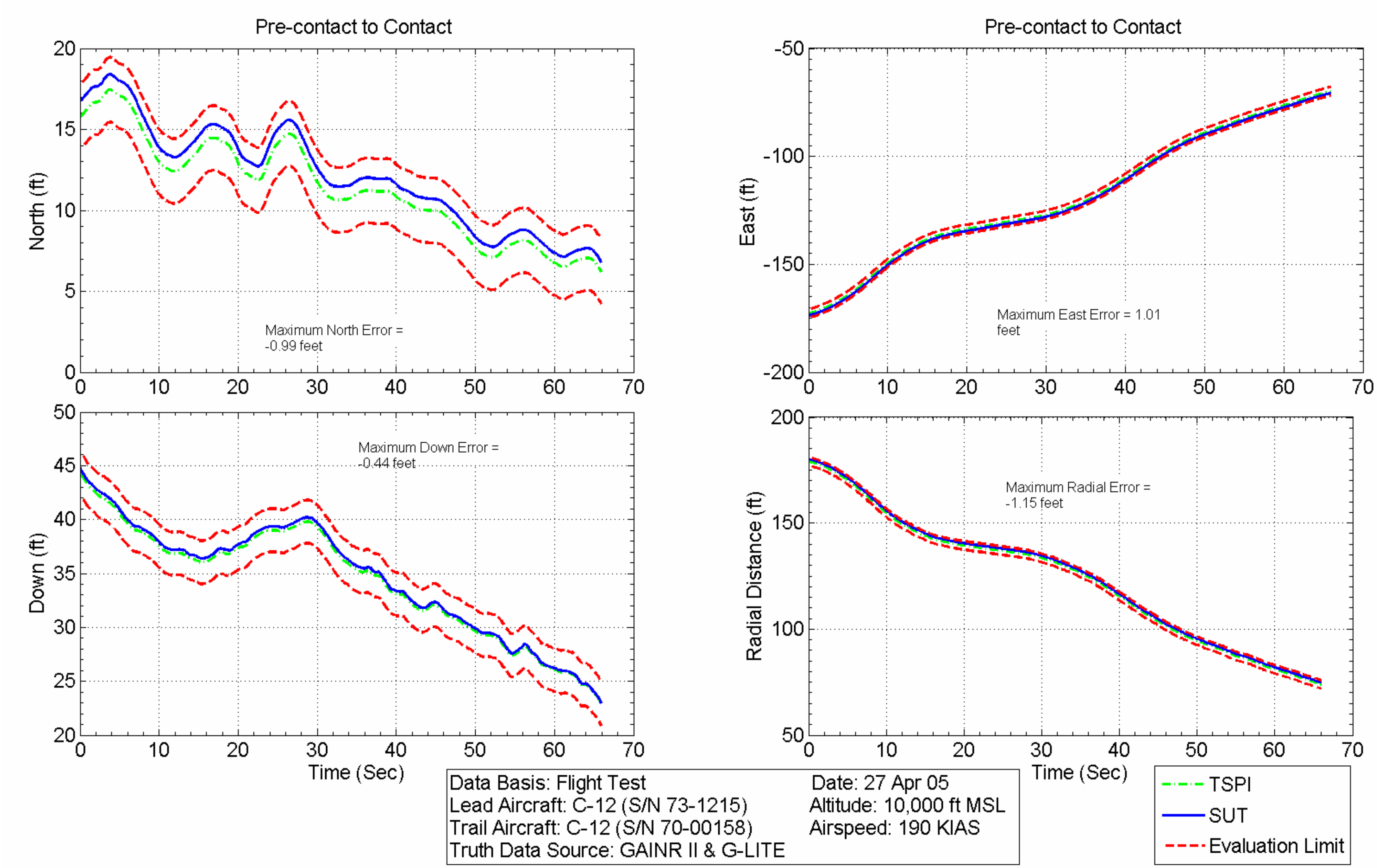

Figure D-13: Relative GPS Position Comparison between SUT and truth source during the Pre-contact Position to Contact Position transition

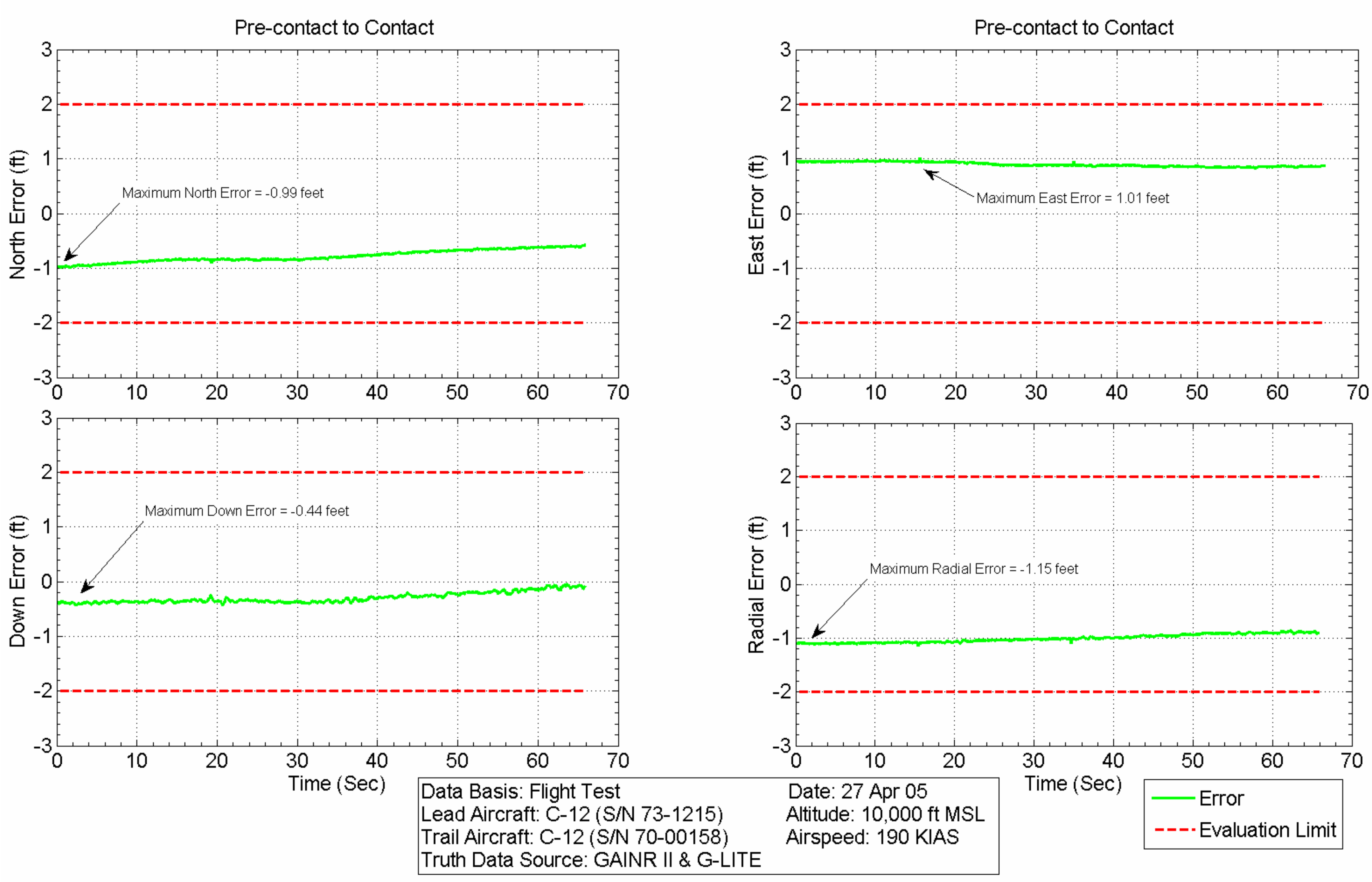

Figure D-14: Relative GPS Position Error during the Pre-contact Position to Contact Position transition

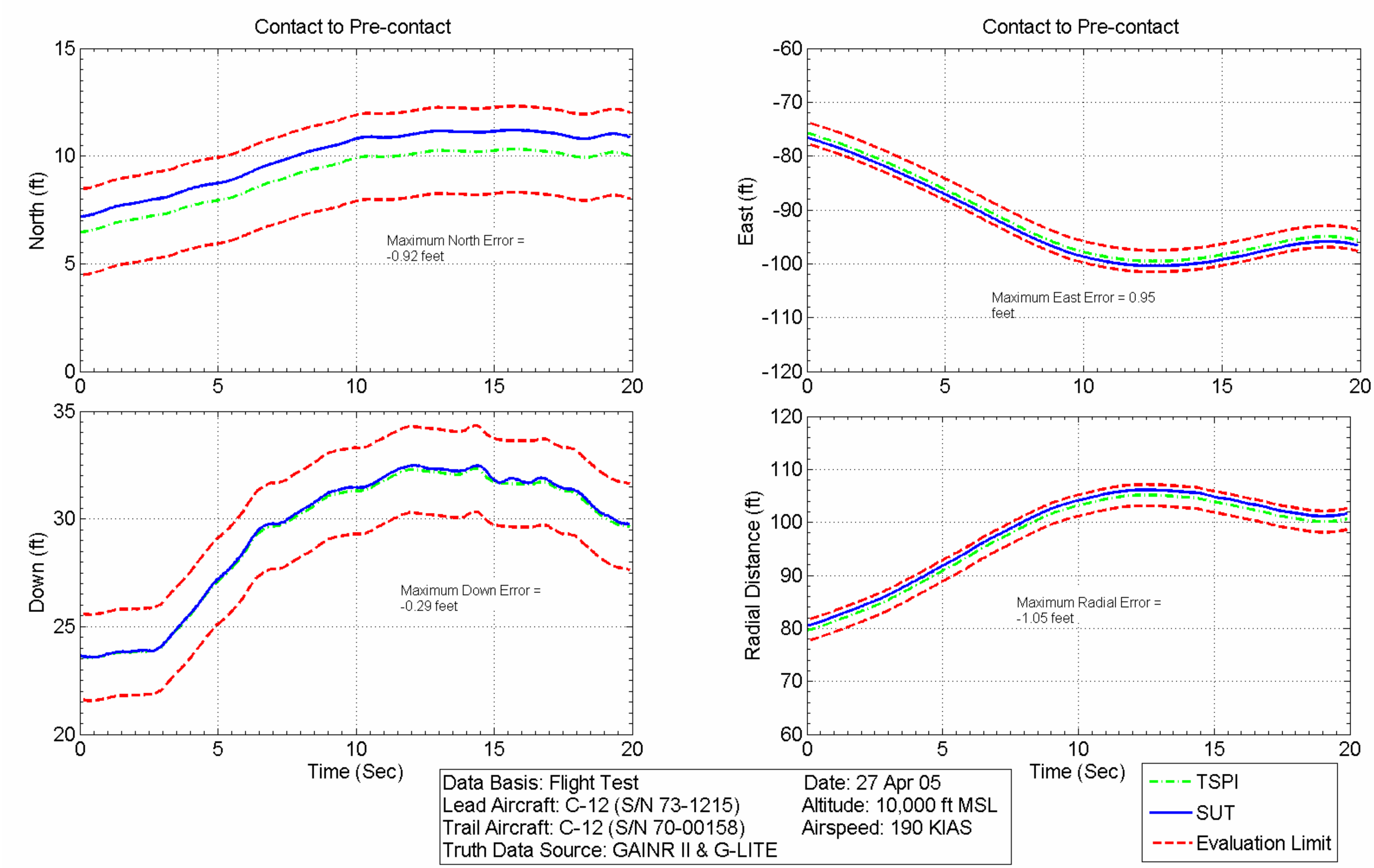

Figure D-15: Relative GPS Position Comparison between SUT and truth source during the Contact Position to Pre-contact Position transition

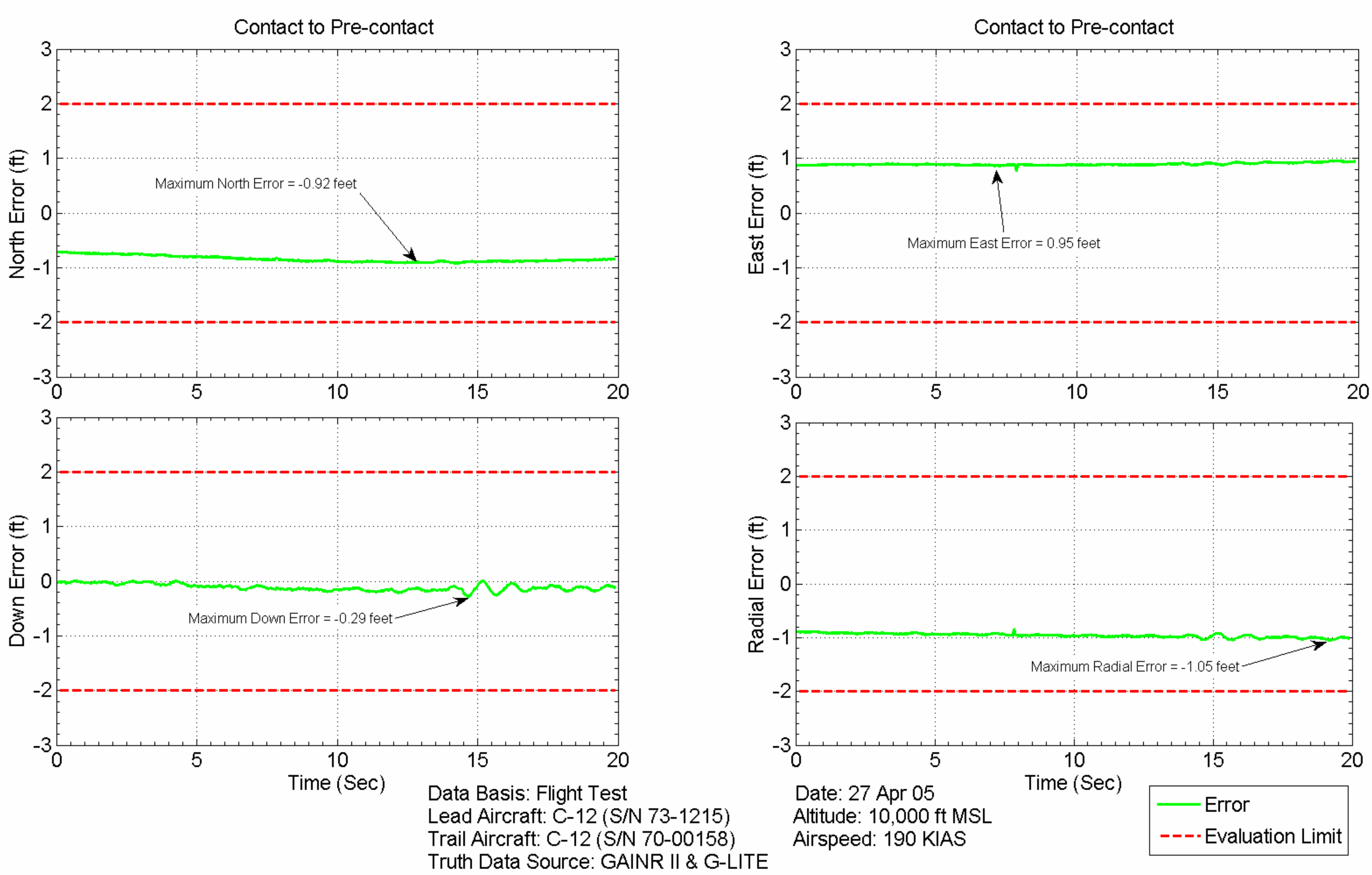

Figure D-16: Relative GPS Position Error during the Contact Position to Pre-contact Position transition

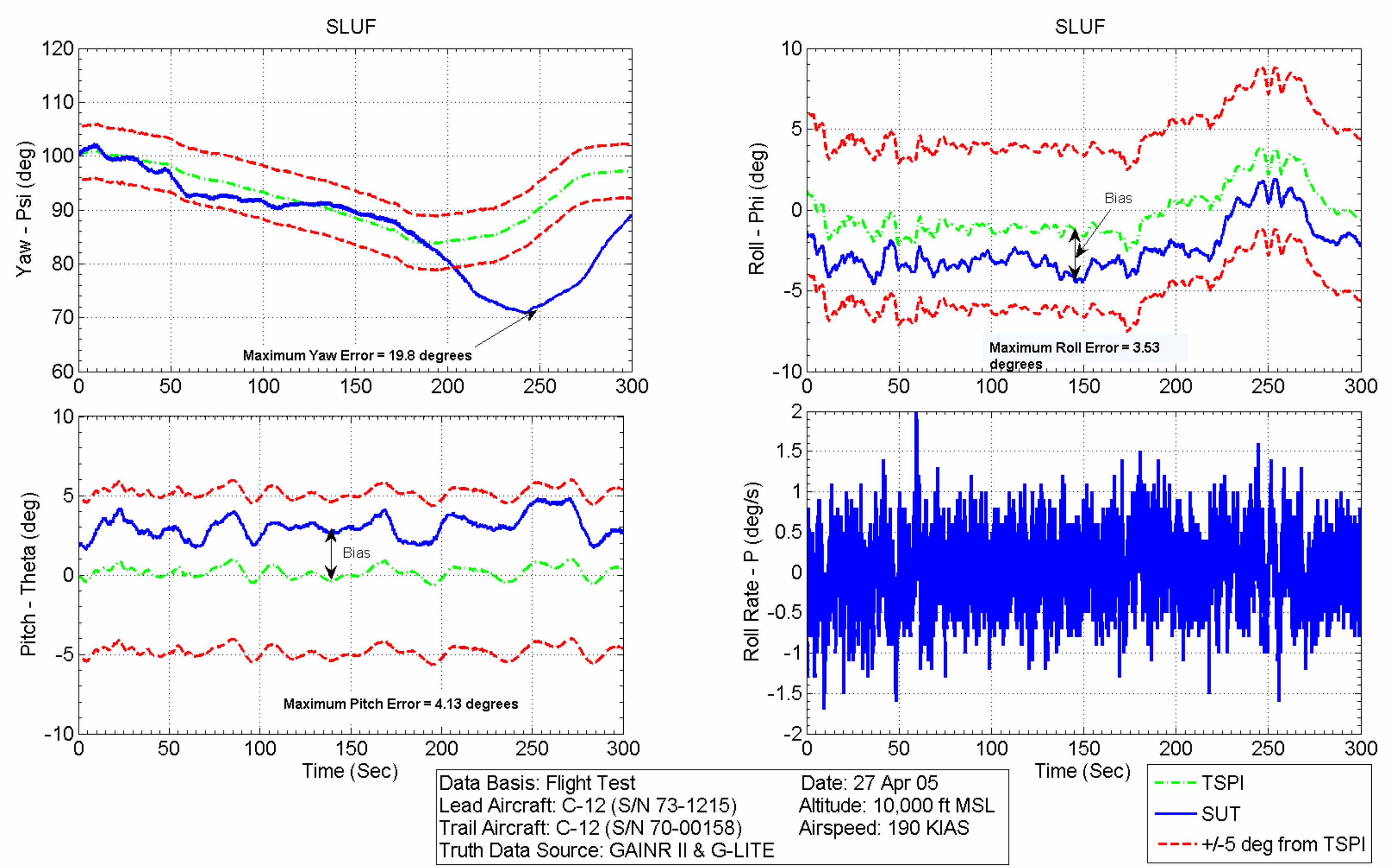

Figure D-17: MEMS IMU Error during SLUF

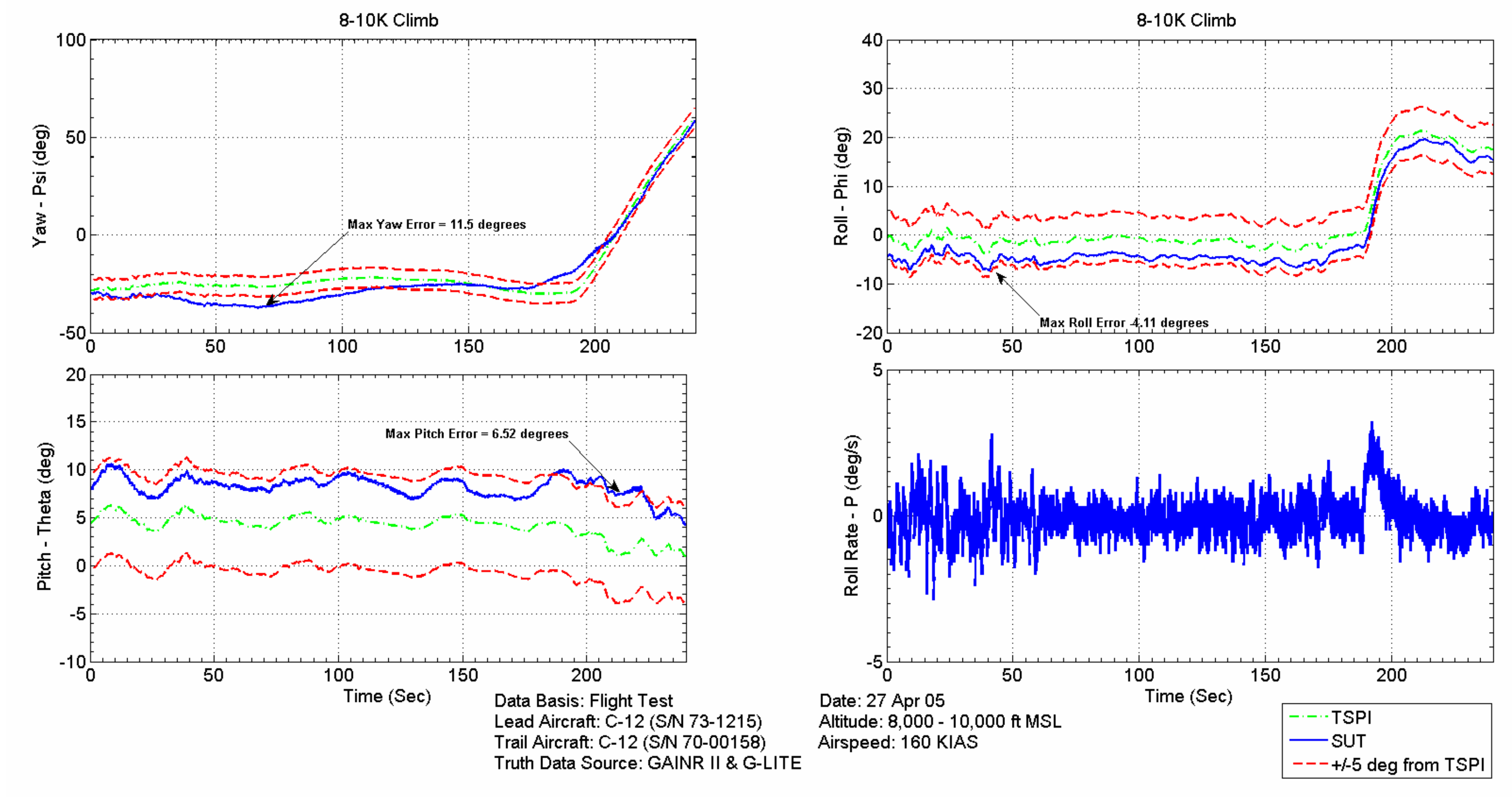

Figure D-18: MEMS IMU Error during Climb from 8,000 PA to 10,000 PA

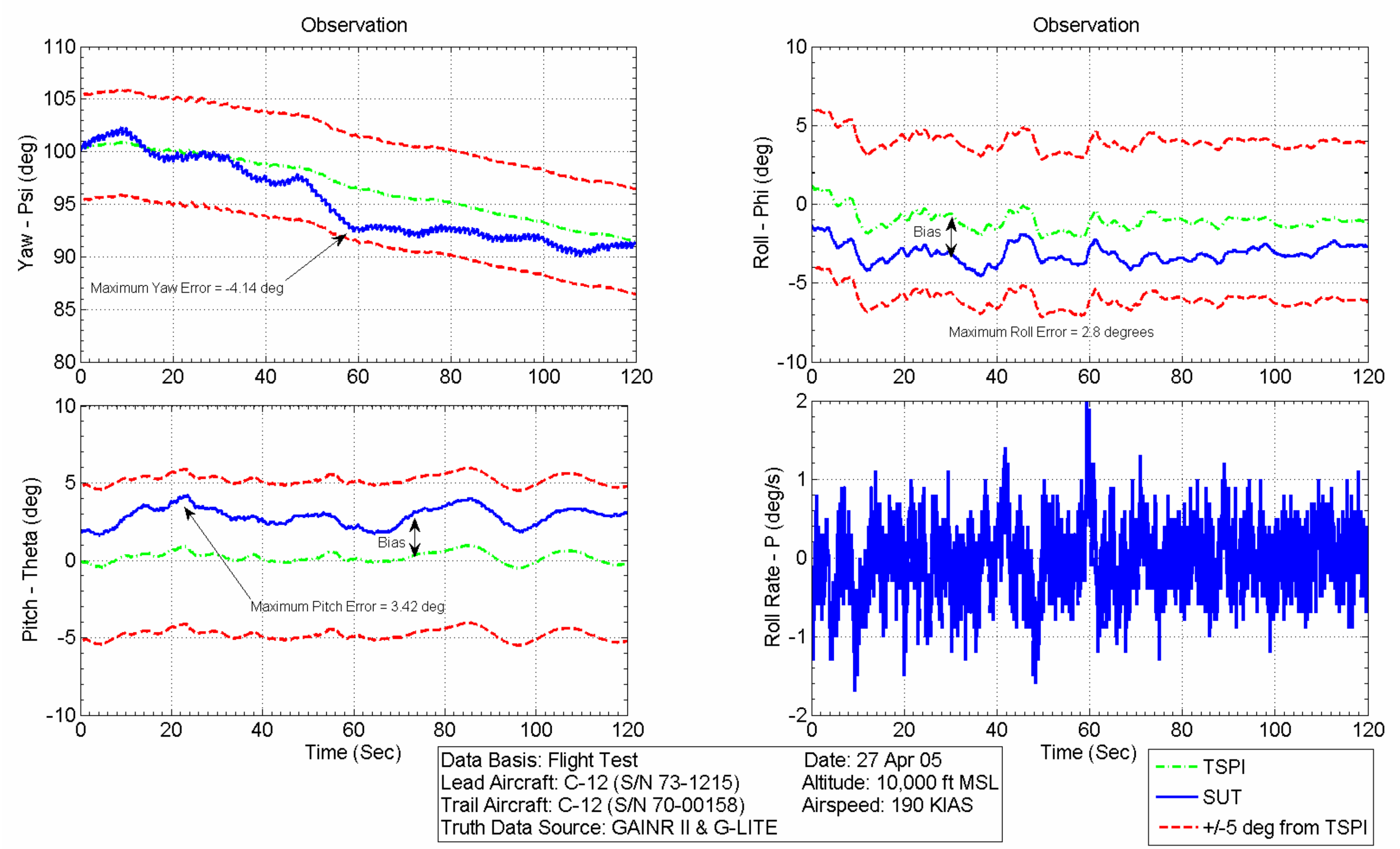

Figure D-19: MEMS IMU Error at the Observation Position

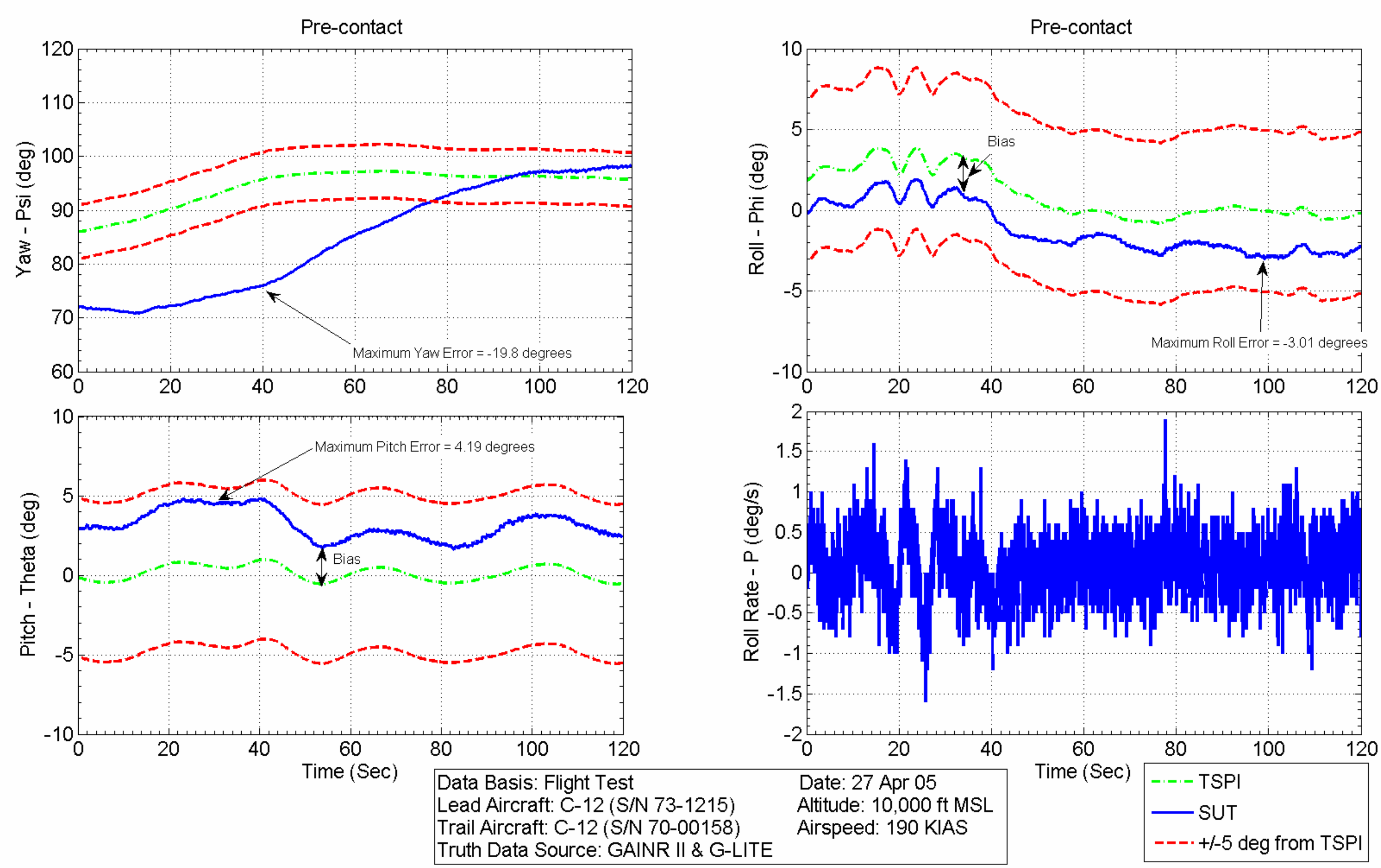

Figure D-20: MEMS IMU Error at the Pre-contact Position

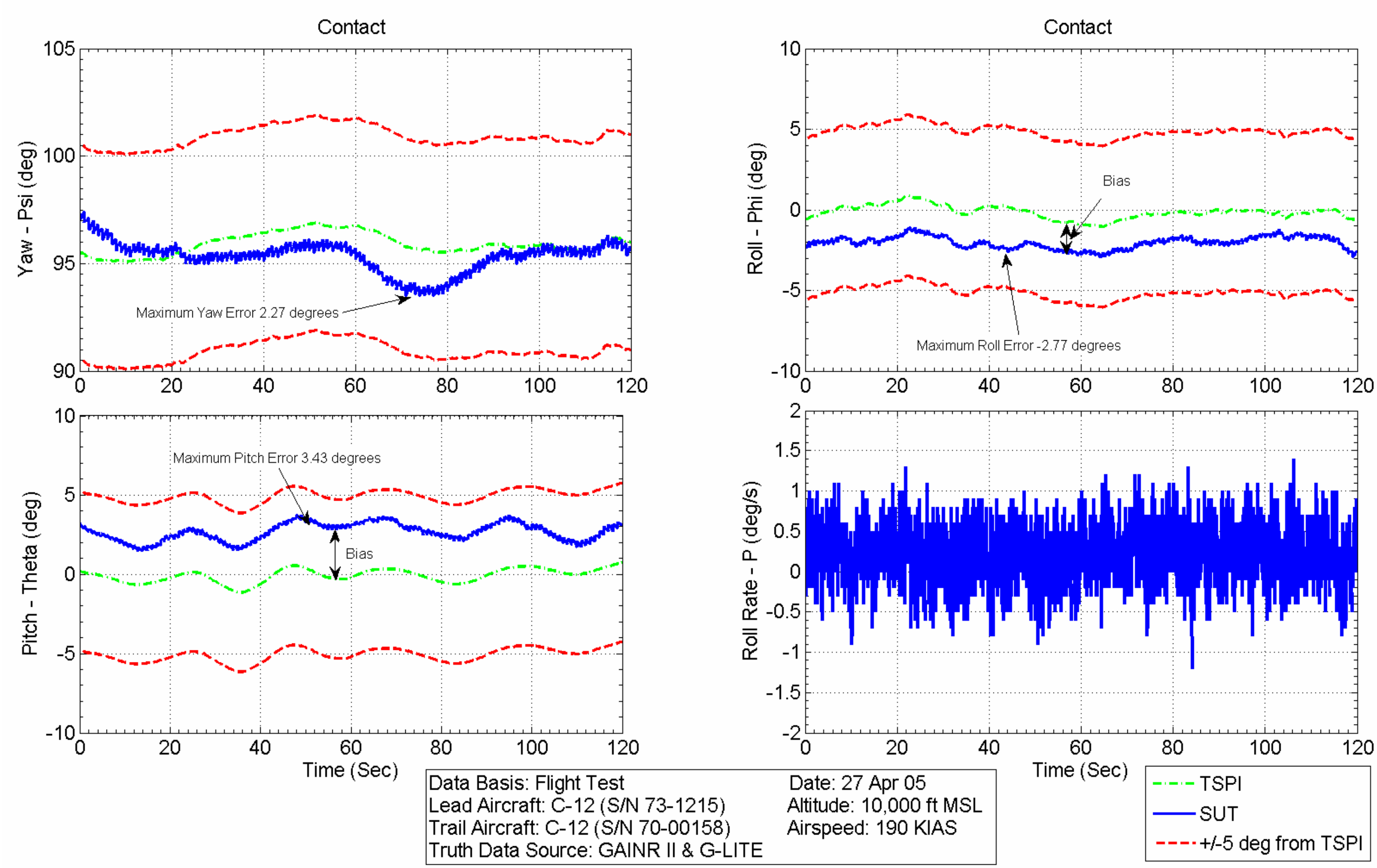

Figure D-21: MEMS IMU Error at the Contact Position

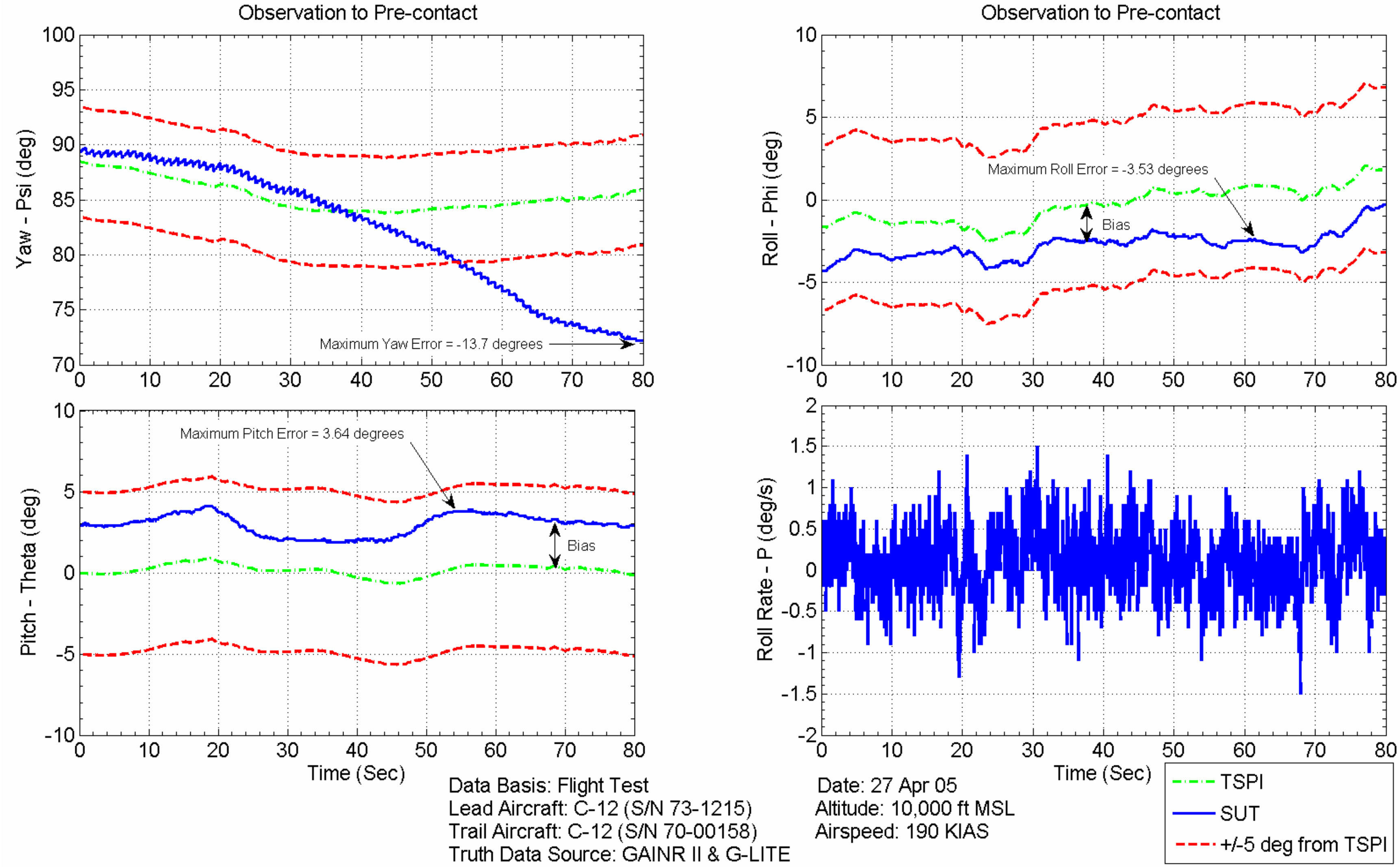

Figure D-22: MEMS IMU Error during the transition from the Observation Position to Pre-contact Position

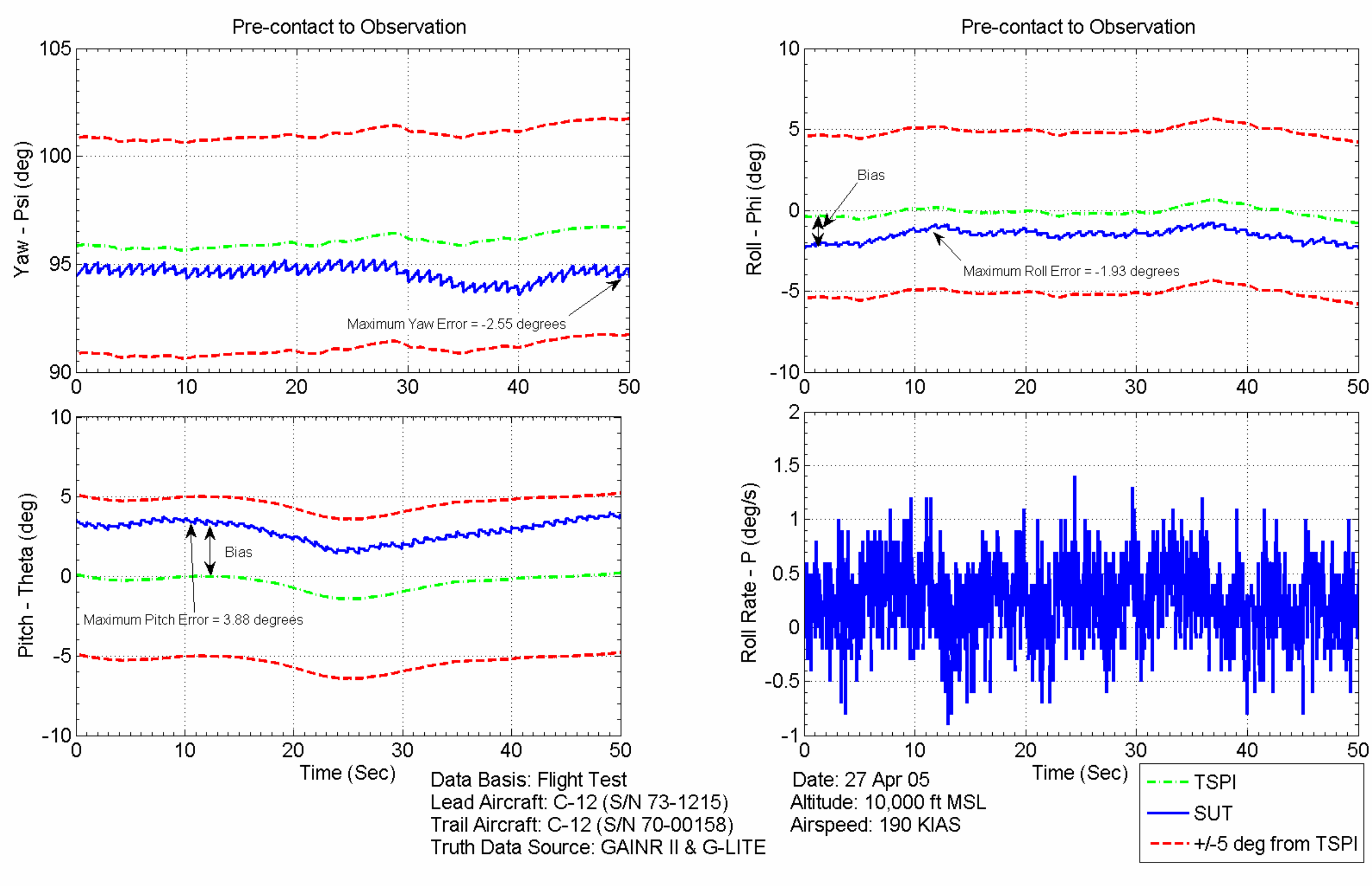

Figure D-23: MEMS IMU Error during the transition from the Pre-contact Position to Observation Position

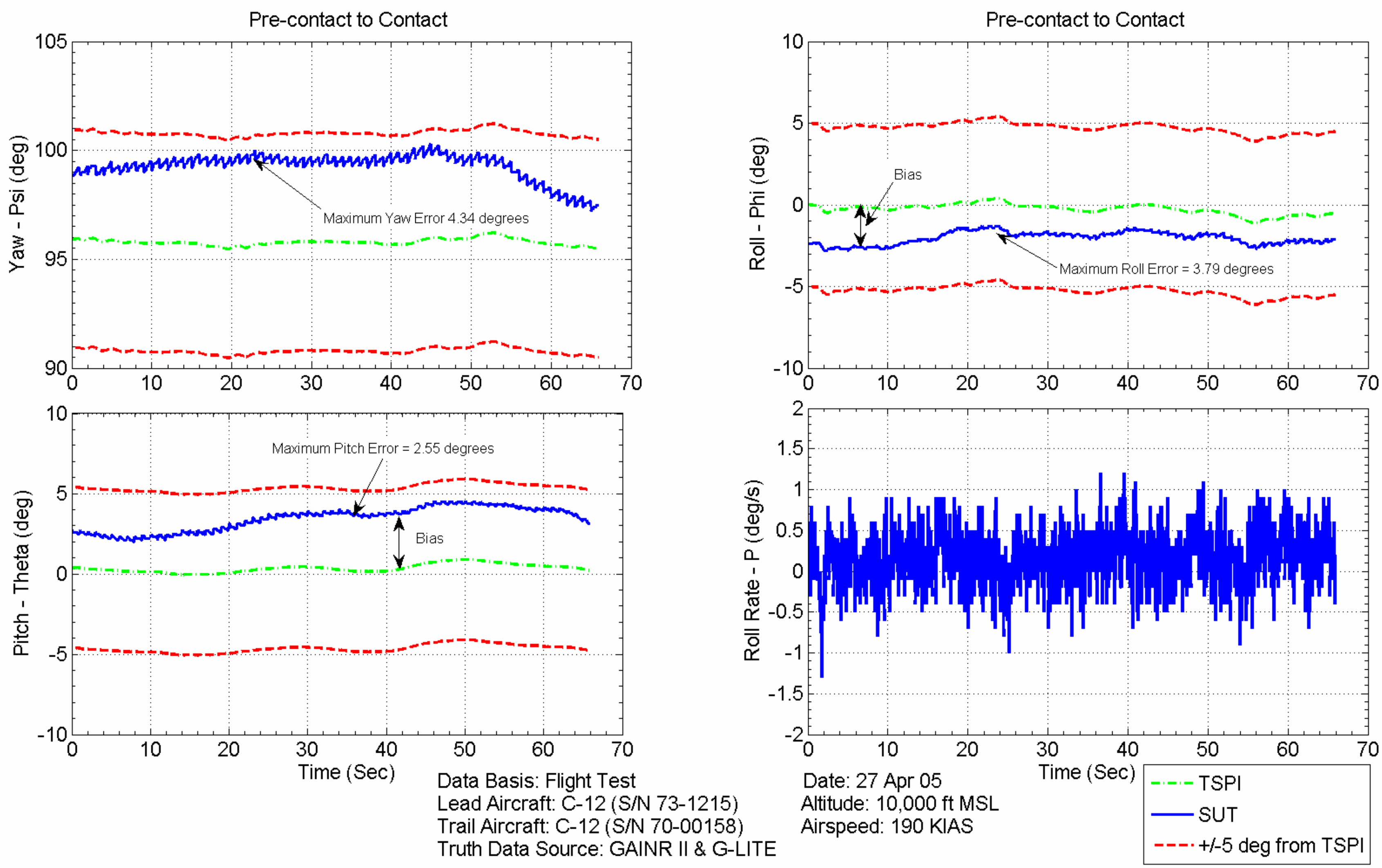

Figure D-24: MEMS IMU Error during the transition from the Pre-contact Position to Contact Position

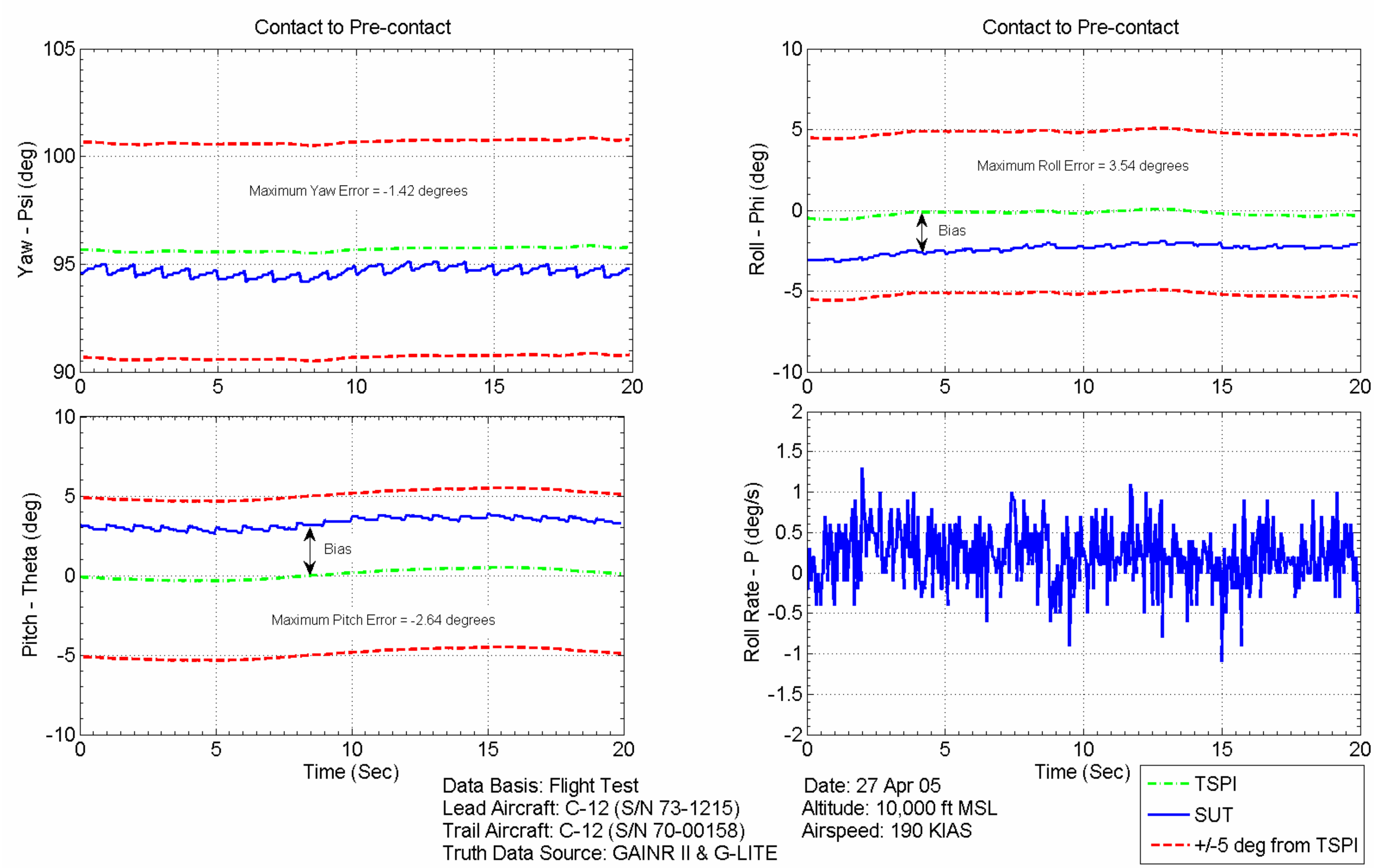

Figure D-25: MEMS IMU Error during the transition from the Contact Position to Pre-contact Position

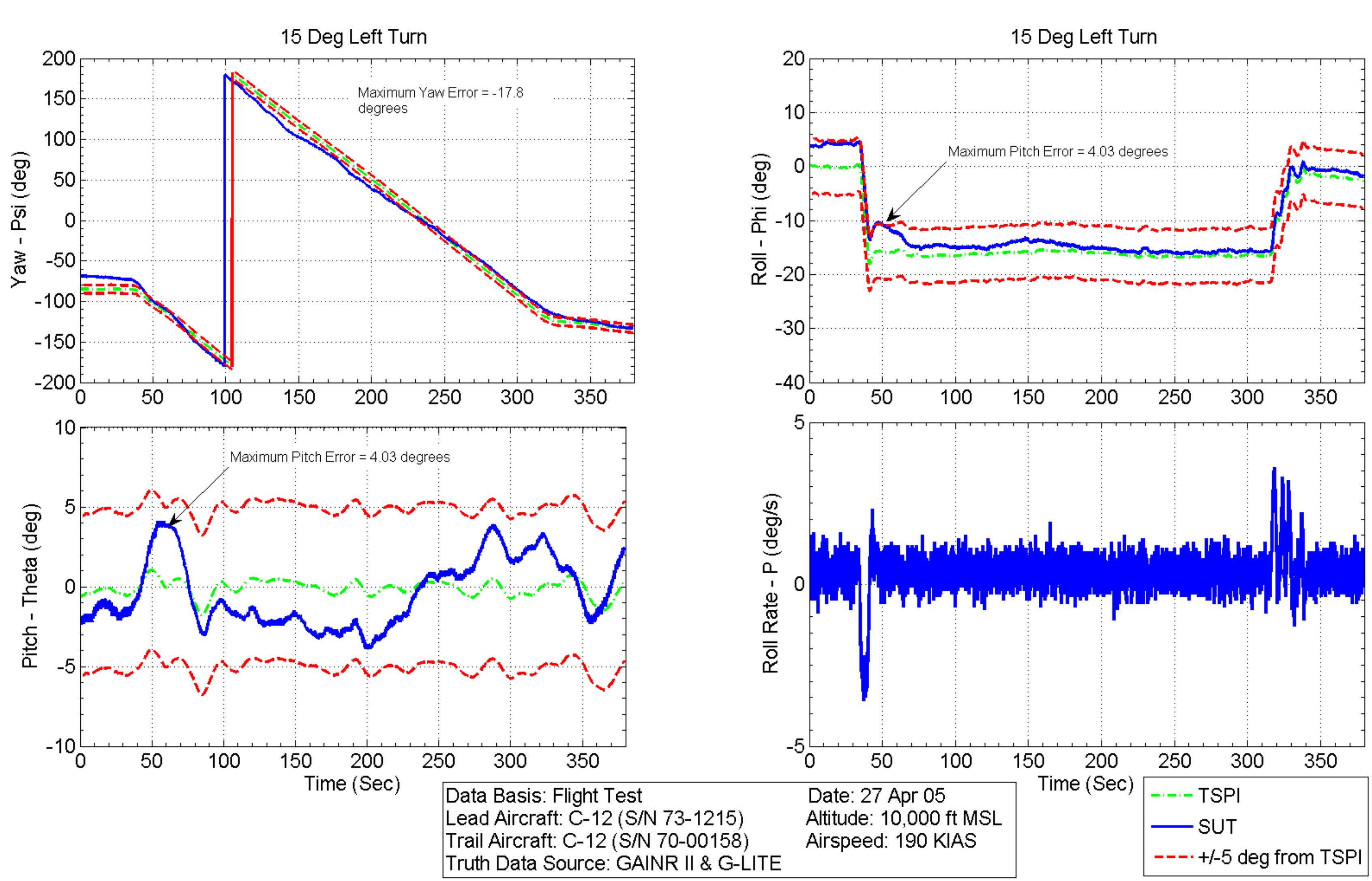

Figure D-26: MEMS IMU Error during 15-Degree Bank Left Turn for 360 Degrees

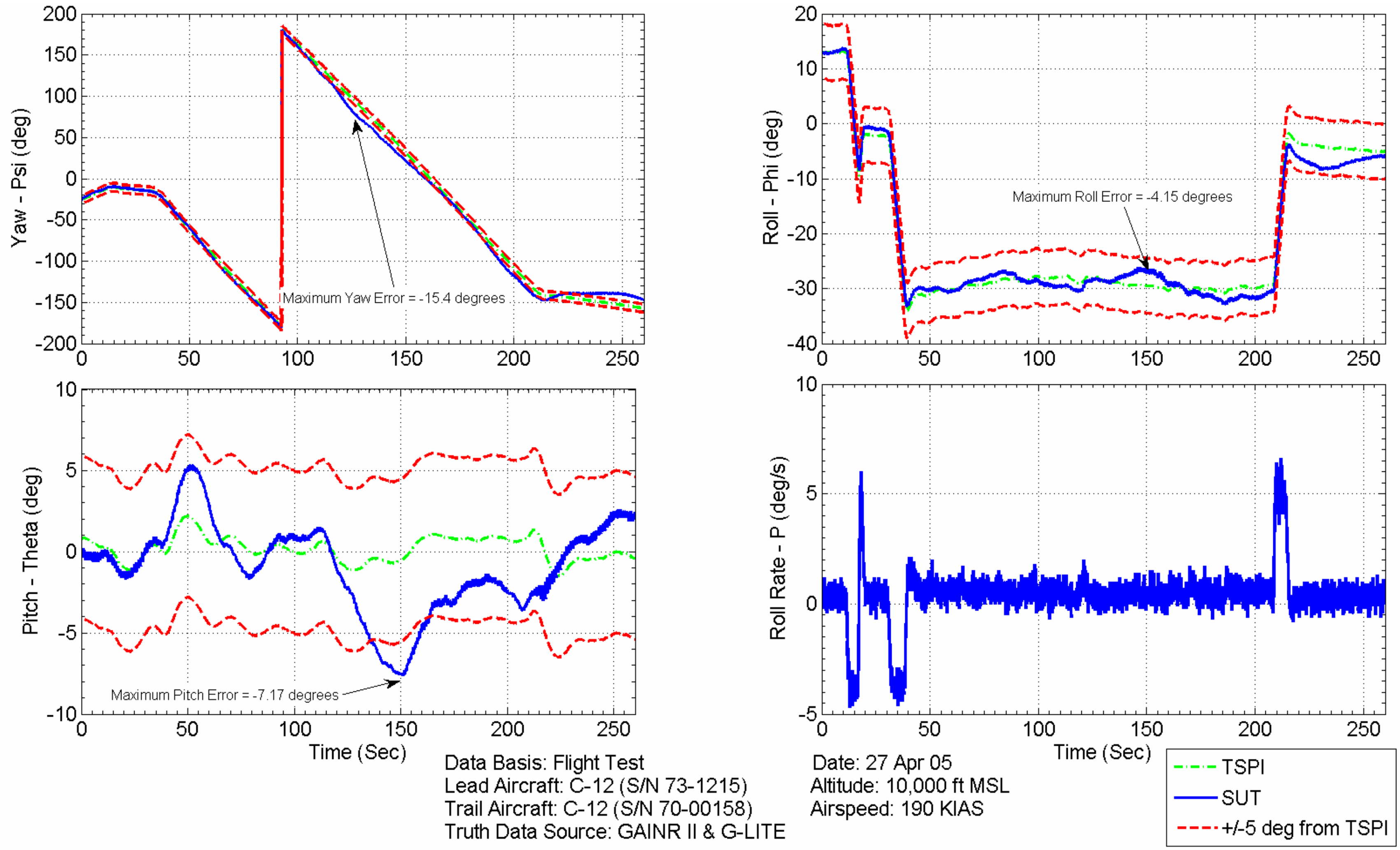

Figure D-27: MEMS IMU Error during 30-Degree Bank Left Turn for 360 Degrees

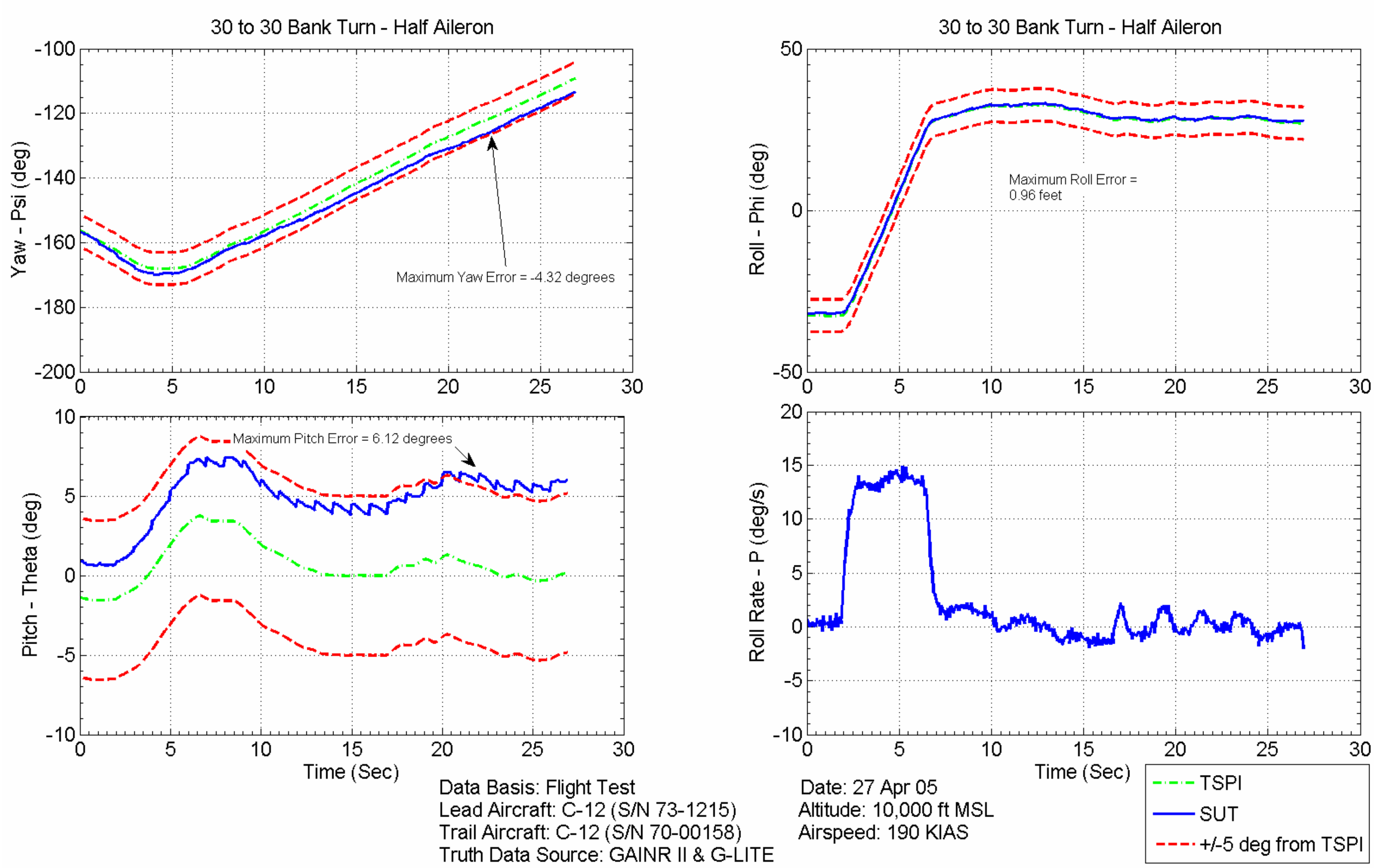

Figure D-28: MEMS IMU Error during 30 Degrees to 30 Degrees Bank-to-Bank Roll

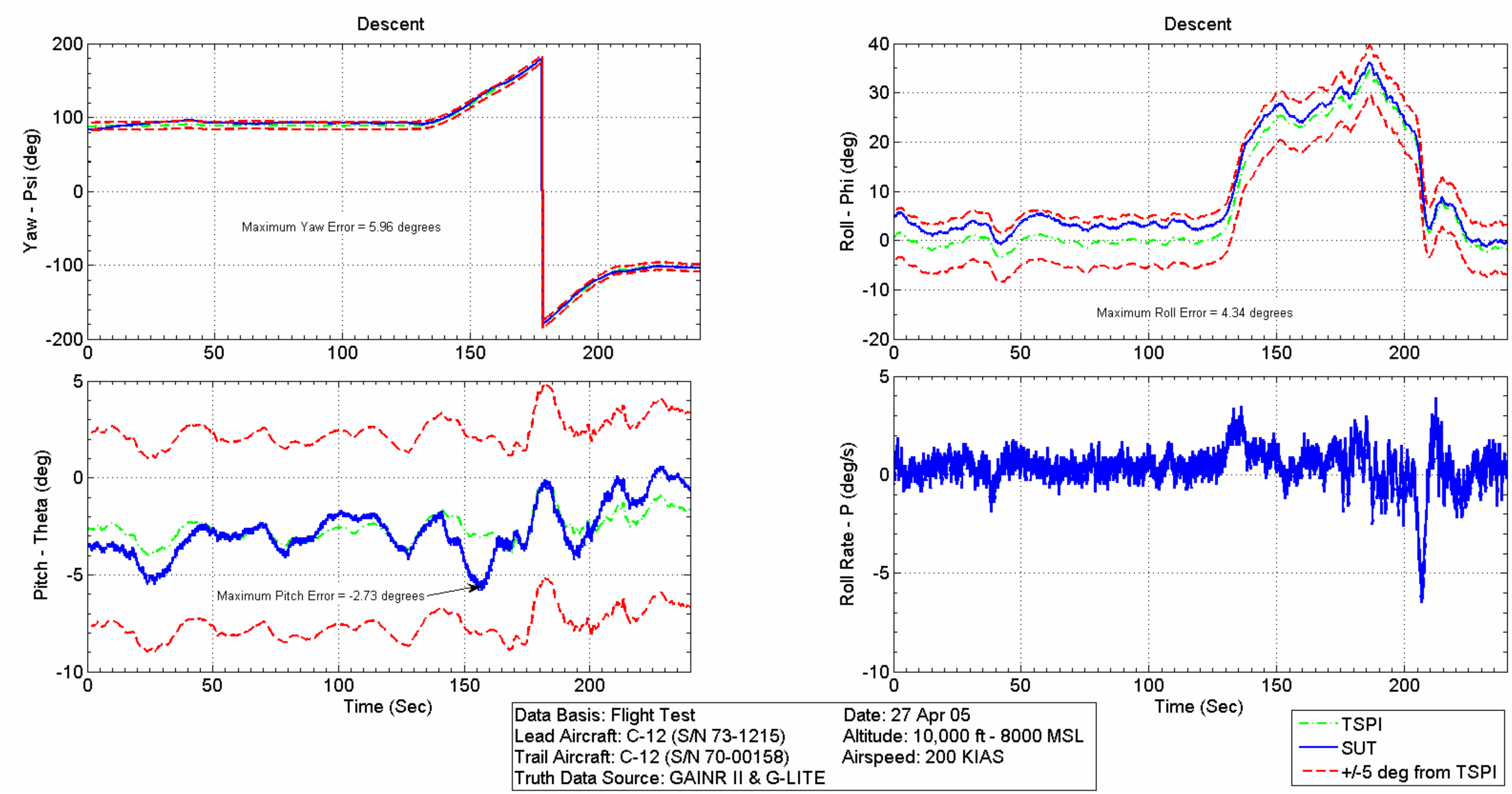

Figure D-29: MEMS IMU Error during descent from 10,000 PA to 8,000 PA

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APPENDIX E – LIST OF ACRONYMS

AFFTC	Air Force Flight Test Center
AFIT/ENG	Air Force Institute of Technology Department of Electrical & Computer Engineering
EGI	Embedded GPS/INS
GAINR	GPS Aided Inertial Reference
IMU	Inertial Measurement Unit
MEMS	Micro-Electro-Mechanical System
MFM	Modification Flight Manual
MOS	Modification Operational Supplement
PA	Pressure Altitude
RTO	Responsible Test Organization
SLUF	Straight & Level Unaccelerated Flight
SUT	System Under Test
TIM	Technical Information Memorandum
TMP	Test Management Project
TPS/DO	Test Pilot School Operations Division
TPS/EDT	Test Pilot School Education Division, Test Management Branch
TSPI	Time, Space, Position Information
TW	Test Wing
UAV	Unmanned Aerial Vehicle
Δ	Delta
φ	Roll Angle

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APPENDIX F – LESSONS LEARNED

DESIGN OF EXPERIMENTS – Design of experiments (DOE) principles were used to develop a systematic plan for determining the primary factors effecting the system position accuracy. Unfortunately, due to the cancellation of the final flight due to hardware problems, the DOE plan was not executed. However during the planning process, the test team was able to capture these lessons learned.

- **LL: Balance efficient flight test with DOE principles.** The original test plan alternated test points at 10K MSL and 17K MSL for randomization purposes. As this climb takes ~10 minutes in a C-12, this did not lead to efficient testing. The test points were later modified to facilitate test point efficiency at the expense of randomization.
- **LL: A test matrix expands unnecessarily when there are many factors and only a limited number of flights.** DOE seemed to lend itself more to being able to reduce data as testing is completed sequentially, rather than reducing a large block of data points at one time.
- **LL: When beta testing, it is more important to identify large problems with the system under test, rather than use DOE to identify small factors that affect system performance.** DOE could have been a useful tool to identify the factors leading to the large problems identified during the testing. In our test program, the cause of the problems was usually easy to recognize without DOE.

MODIFICATIONS - Due to the aggressive test schedule, the system under test (SUT) hardware and software was not available at the beginning of the scheduled flight test period, which ultimately prevented the completion of the planned flight test sorties. After problems with the GPS receiver were suspected on flight 2, AFIT requested replacing the GPS receiver card in the lead system. Unfortunately, the hardware change was requested by system experts at AFIT at Wright Patterson AFB, Ohio and performed by modification personnel at Edwards AFB, California. This led to a modification that rendered the system inoperable prior to the third flight which was not able to be flown due to the condensed flight window of Test Pilot School.

- **LL: Plan time in the modification schedule to correct problems encountered after initial system modification**

GROUND CHECKOUT EQUIPMENT – Ground checkout equipment was brought by AFIT to support the ground checkout and preparation for first flight. However, this equipment was not available to checkout the modifications made between flights to ensure a successful modification.

- **LL: Ensure the necessary ground checkout equipment is available to support bench/ground test of all modifications.**

ON-SITE SYSTEM EXPERTICE - The on-site support provided by an Air Force Institute of Technology (AFIT) representative during the modification checkout, ground testing, and first flight was invaluable. Unfortunately this representative was not available to provide support throughout the flight window. Due to the lack of system maturity, no

developer-provided instructions, instrumentation, or software existed either to support ground testing, or SUT troubleshooting between flight tests.

- **LL: Plan to have system experts on-site to support system software and hardware updates between flights when detailed instruction is not available.**

ON/OFF SWITCH - The black box system under test installed on each aircraft did not have an on/off switch. Thus, the system had to be plugged in and unplugged to power it up, shut it down, or reboot it. Prior to one of the flights, the system was plugged in, indicating that it was running during other non-test USAF Test Pilot School curriculum sorties using the data acquisition system.

- **LL: For follow-on testing, include an on/off switch in the aircraft modification to ensure the system is off when not in use by the test team.**

POWER CARTS - Only one power cart was available to support ground checkout of the system prior to flight two which resulted in performing the pre-flight checkout of a new software load with the engines running. During the checkout, the test team determined that the IMU alignment needed to be performed with the engines off. Thus the pilots had to shut down the engines and swap the aircraft that the power cart was hooked up to. It was later discovered that C-12 maintenance only had one power cart reserved for their use and they had to borrow a second cart when requested. The successful flight 1 ground checkout and flight 3 ground checkout which identified the unsuccessful modification proceeded much smoother with two power carts.

- **LL: Conduct as much preflight checkout on the ground using ground power as is practical.**

DATA REDUCTION – Matlab was the primary data reduction tool used for this test program. The USAF TPS license for Matlab required that a computer using Matlab be connected to the local area network for Matlab to run. This constraint prevented data reduction from being accomplished for a week and a half following the end of the fly window when the test team was TDY.

- **LL: Ensure data reduction tools are in place to meet test reporting deadlines.** For this TMP, it would have been helpful to obtain a limited number of Matlab licenses to enable data reduction when not connected to the USAF TPS network.

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